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Manufacturing Technology and Application of Titanium Alloy Wire Rod to Deep-Sea Cable

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Abstract:

Titanium has excellent seawater corrosion resistance and high specific strength, so that it is an ideal material for the armor of cables used in marine environments. A 12,000-m long titanium alloy-armored cable for use in investigating the deepest trenches of the ocean was developed by using β titanium alloy wire rod for the first time in the world. In this paper, material selection for the cable wires is briefly referred to, and the cable manufacturing process comprising wire rod rolling, shaving, drawing, and cable fabrication is described. Also introduced are the actual production results by the process centering on the mechanical properties of the wire rod, wire, and cable obtained.

1. Introduction

As the environmental problems are coming into the spotlight recently, there is mounting need for oceanographic surveys. One method of oceanographic observation consists of attaching a sensor or water bottle at the end of a cable and suspending it from a ship or towing it with a ship. This method is employed by the Meteorological Agency and the Ocean Research Institute, University of Tokyo. The cable is usually armored with galvanized steel wires. Since the galvanized steel wire armor is low in specific strength (tensile strength/specific gravity ratio), the cable can be used only to a depth of about 6,000 m at most. As the armor is low also in seawater corrosion resistance, it is coated with rust inhibitor or otherwise is rusted. The rust inhibitor or rust is apt to contaminate water samples taken.

Survey in the world's deepest trenches of the 10,000-m class calls for a cable that clears the above two problems. Attention was focused on titanium alloy as a solution to these problems. The world's first titanium alloy-armored cable was adopted on the oceanographic research ship "Hakuho Maru" of the Ocean Research Institute, University of Tokyo, completed in 1988. The cable was jointly manufactured by Furukawa Electric, Suzuki Metal Industry, and Nippon Steel. The results of the cable manufacture are introduced here.

2. Selection of Titanium Alloy Material

The cable armor material is required to have high tensile strength comparable to the 1,373-N/mm^2 level of steel wire and a cold reduction of area on the order of 90% (because wire is drawn to a final diameter of about 1 mm). The mechanical properties of available titanium alloys are listed in **Table 1**.

Titanium alloys generally come in α, $\alpha + \beta$, and β types. Comparing these three types in the light of the required material properties, the α and $\alpha + \beta$ types are insufficient in both strength and formability, whereas the β type satisfies both requirements. Cold working can provide Ti-3Al-8V-6Cr-4Mo-4Zr (commonly

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Table 1 Mechanical properties of titanium alloys

Alloy type		Mechanical properties					Tensile strength after strengthening (N/mm^2)
		Finished condition	0.2% yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Finished conditon	
α type	Ti-5Al-2.5Sn, etc.	Ann.	≧1,109	≧1,177	≧10	—	—
$\alpha + \beta$ type	Ti-6Al-4V	Ann.	≧1,177	≧1,275	≧10	STA	≧1,472
	Ti-6Al-2Sn-4Zr-2Mo, etc.	Ann.	≧1,226	≧1,324	≧ 8	STA	≧1,619
β type	Ti-3Al-8V-6Cr-4Mo-4Zr	STA	≧1,570	≧1,668	≧ 6	CW	≧1,766
	Ti-15V-3Cr-3Al-3Sn, etc.	STA	≧1,373	≧1,422	≧ 7	CW	≧1,570

Ann.: Annealed, STA: Solution treated and aged, CW: Cold worked by reduction of area of 90% or more

referred to as Beta C) with the highest strength of the β alloys. Beta C was thus selected as the armor material of the water sampling cable.

3. Manufacturing Methods

3.1 Chemical composition

The chemical composition of Beta C is typically shown in **Table 2.**

3.2 Manufacturing process

Fig. 1 shows the whole manufacturing process from material procurement to cable fabrication. In the joint manufacture, the rod was rolled by the Hikari Works of Nippon Steel, drawn into wire by Suzuki Metal Industry, and fabricated into the armored cable by Furukawa Electric.

Since Beta C was difficult to procure in Japan, 106 mm square and 5,000 mm long Beta C rod billets were purchased from TIMET Corporation of the United States. Each billet was hot rolled into a 8.5 mm rod at the fully continuous rod mill of Hikari Works. The oxide scale and the hardened layer or alpha case formed in the surface of the as-rolled rod were removed by salt bath descaling and acid pickling. The alpha case must be completely removed because if left unremoved, it may cause cracks in the surface of the rod in the cold working process. The cleaned rod was cold rolled by a reduction rate of about 10% by vertical and horizontal (VH) rolls, collectively called the roller die, and improved in roundness. It was then passed through a shaving die to remove surface defects. The rod work hardened in the process was annealed in a vacuum annealing furnace.

Suzuki Metal Industry lubricated the annealed rod and drawn it into 1.04 mm wire on a multi-block wire drawing machine. The wire was spirally preformed in a special manner so that the cable armor made from the wire would not slacken in service.

Table 2 Chemical composition of Beta C (wt%)

Al	Zr	Mo	V	Cr	Fe	C	N	H	O	Ti
3.5	3.8	3.7	7.6	6.2	0.12	0.01	0.01	0.01	0.09	Rem.

Furukawa Electric wound the wire around separately produced cable conductors to assemble a 8.15 mm diameter armored cable.

3.3 Rod rolling

3.3.1 Specifications of rod mill

Table 3 shows the equipment specifications of the rod mill. Billets are available in two sizes of 150 mm square and 106 mm square. The 106 mm square size is used as standard for titanium because titanium products are generally made in small lots and many sizes. The rod mill consists of a roughing mill (8 stands), intermediate mill (8 stands), prefinishing mill (PFM) (4 stands), and finishing mill (FM) (10 stands). The 30 stands are arranged in tandem. A repeater is installed between the intermediate mill and the prefinishing mill for tension adjustment. The prefinishing mill and the finishing mill are VH roll block mills suited for high-speed rolling because the rod is not twisted during rolling.

3.3.2 Rolling conditions

Beta C was heated in air at the set temperature of 1,140±10°C. Generally, titanium suffers marked surface oxidation when heated, and therefore should be heated at the lowest possible temperature. The heating temperature of 1,140°C was selected from considerations of the rolling mill capacity. **Fig. 2** shows the hot tensile strength of Beta C determined by the Gleeble test. The 1,140°C tensile strength is about 10 N/mm^2 for commercially pure titanium and about 150 N/mm^2 for Beta C. This high

Table 3 Specifications of rod mill

Item	Specification	
Billet size	150 mm □ × 12,000, 6,000 mm 106 mm □ × 12,000, 6,000 mm	
Rod size	Maximum: 34.0 mmϕ Minimum: 5.5 mmϕ	
Rolling speed	Maximum: 87 m/s (for 5.5 mmϕ rod)	
Rolling mill	Roughing mill Intermediate mill Prefinishing mill (4VH) Finishing mill (10VH) Repeater	8 8 1 1 1

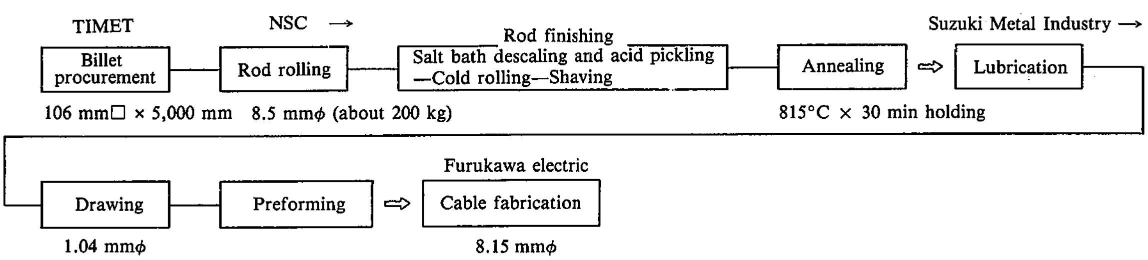


Fig. 1 Cable manufacturing process

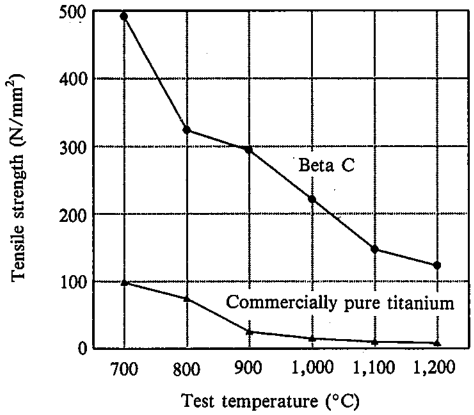


Fig. 2 Gleeble test results

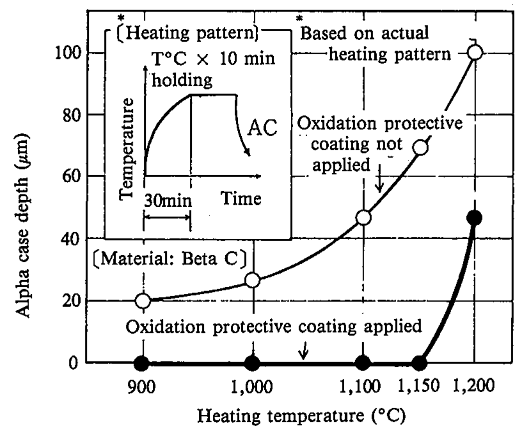


Fig. 3 Effect of heating temperature on depth of alpha case in Beta C

Table 4 Composition of high-temperature oxidation protective coating (wt%)

SiO_2	Fe_2O_3	Al_2O_3	CaO	TiO_2	$(NH_4)_2HPO_4$
58.8	8.0	7.8	1.4	0.25	23.75

strength of Beta C imposes a constraint on the roughing mill.

Thirteen billets were charged per batch into the reheating furnace. One of the billets was a short billet (1,000 mm long), which was used for the purpose of heating temperature control. Thermocouples were buried in the surface and center of the temperature control billet. When the two thermocouples read the set temperature, the other billets were discharged from the reheating furnace by the pusher, and were rolled to 8.5 mm diameter rods. The rolling speed was set at 40 m/s, which is as high as for stainless steel, in order to alleviate the rolling load increment due to the temperature drop during rolling. No roll cooling water was used during the rolling operation.

3.3.3 High-temperature oxidation protective coating

An oxidation protective coating is applied as a standard practice to titanium rod billets in order to minimize rolling defects arising from oxide scale during heating. Commercially pure titanium is heated at about 700°C, and the SiO_2-Al_2O_3-based oxidation protective coating applied is effective up to about 900°C. In this project, Beta C was heated to a higher temperature of 1,140°C and treated with a special SiO_2-$(NH_4)_2$ HPO_4-Fe_2O_3 oxidation protective coating. The composition of the coating is as shown in **Table 4.**

3.4 Rod shaving conditions

The shaving die was made from tungsten carbide (WC), a cemented carbide conventionally used for high-strength steels like valve spring steel, and was coated with TiCN. The rod was shaved at a low speed of 20 m/min to decrease the cutting resistance and reduce the chipping occurrence of the die.

3.5 Wire drawing conditions

In the wire drawing of titanium alloy rods, it is extremely difficult to ensure good lubrication. Generally, an oxide film (oxide scale) on the order of several micrometers is imparted on the rod surface. This method hardens the surface layer of the rod through the diffusion of oxygen, which makes it difficult to cold work the rod with a high reduction of area. The result is that high strength cannot be obtained. New wire drawing technology without oxide scale lubrication was developed and brought to practice by which the rod is drawn into wire at a reduction of area of about 90%.

3.6 Cable fabrication conditions

When an armored cable is tensioned, it rotates as the armor tends to untwist. If its rotating tendency is large, the armored cable may be kinked and damaged by the heaving of the ship from which it is suspended. To prevent this damage, Beta C wire (armor) was arranged in two layers around the core of the cable, and the armor wires in the two layers were twisted in opposite directions to minimize the rotation of the resultant armored cable.

4. Results of Manufacture

4.1 Performance investigation of oxidation protective coating

Fig. 3 shows the results of investigation made into the performance of the SiO_2-$(NH_4)_2$ HPO_4-Fe_2O_3 oxidation protective coating as a step preliminary to the Beta C rod rolling. A 20 mm square specimen was machined from a Beta C billet, coated over a half of one surface with the oxidation protective coating, heated and cooled in air within the temperature range from 900 to 1,200°C, according to the actual heating pattern. The thickness of the alpha case formed in the specimen was measured microstructurally. As a result, the oxidation protective coating was found to be effective up to 1,150°C. At 1,150°C, the alpha case thickness is 70 μm when the oxidation protective coating is not applied, but is practically zero when the oxidation protective coating is applied.

4.2 Results of rod rolling

Twenty-four billets, each weighing about 210 kg, were procured for rod rolling. Using these billets, preliminary testing and commercial mass production were performed, yielding about 2.5 tons of rod products.

4.2.1 Rod size

In the preliminary test, rods were rolled at two levels of roll gap: level A (based on JIS SUS 316) and level B (level A corrected for actual conditions). An oval rod with the out-of-roundness of 1.37 mm was produced at the level A, while a round bar with the out-of-roundness of 0.33 mm was produced at the level B.

Production rolling was performed with the level-B roll gap. The actual rod diameter ranged from 8.31 to 8.72 mm and met the target range of 8.50±0.4 mm.

4.2.2 Rod surface defects and alpha case

Scabs and laps, presumably resulting from the alpha case, were produced on the surface of the rod over the entire length. These

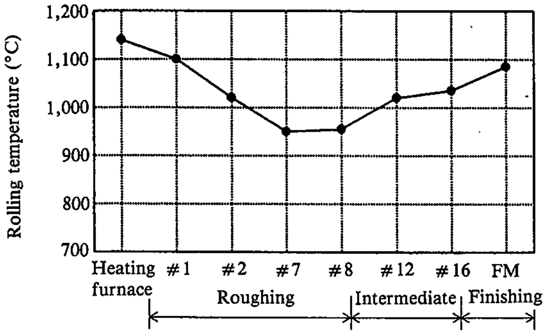


Fig. 4 Change in rolling temperature of Beta C rod

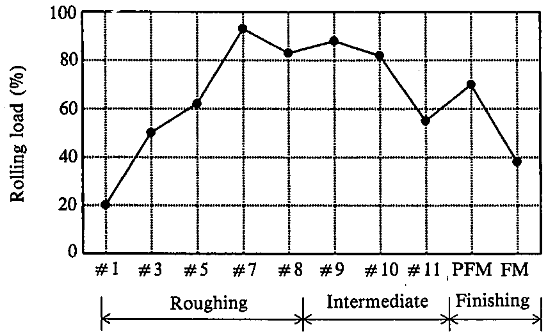


Fig. 5 Change in rolling load of Beta C rod

defects were about 0.10 to 0.20 mm deep and were removed in two shaving operations. The alpha case depth was about 50 to 100 μm according to the result of microstructural observation.

4.2.3 Rolling temperature

Fig. 4 shows a typical change in the billet temperature from the discharge end of the reheating furnace to the delivery end of the finishing mill. The material temperature was the lowest 950°C at the #7 stand, a roughing stand, was raised by the heat of working between the intermediate mill and finishing mill, and reached 1,085°C after the finishing mill.

4.2.4 Rolling load

A typical change in the rolling load from the roughing mill to the finishing mill is shown in **Fig. 5**. The rolling load is the highest 93% on the #7 stand where the rolling temperature is the lowest as noted above, but is less than the permissible range of 100%.

4.3 Results of shaving

The shaving die chipped during the shaving operation and left defects unremoved on the rest of the rod surface. As the roller die was used to correct the diameter of the rod before shaving, true roundness was not secured in the rod, and the resultant uneven shaving imposed an excessive load on the shaving die and chipped it. When the shaved rod was coiled, it uncoiled itself by its springback that was even greater than that of stainless steel rod. The ensuing coil entanglement made continuous coiling difficult to perform. Thus, the rod drawing and coiling methods remain still to be improved. In the end, the rod surface defects due to the chipping of the shaving die were removed by grinding.

4.4 Mechanical properties of rod

A rod cleared of surface defects by shaving or the like was annealed (held at 815°C for 30 min). **Table 5** gives the mechanical properties of the rod product after annealing. As shown, the target properties are satisfied.

Table 5 Mechanical properties of Beta C rod

	Tensile strength (N/mm^2)	Elongation (%)	Reduction of area (%)
Specified value	863-961	≧10	≧40
Measured value	893	24	58

4.5 Mechanical properties of wire

The above-mentioned rod was drawn into wire of 1.04-mm diameter. The mechanical properties of the wire are given in **Table 6**. The tensile strength, the most important property for wire, is 1,697 N/mm^2, which satisfies the specified value of 1,373 N/mm^2 or more.

Table 6 Mechanical properties of Beta C wire

	Tensile strength (N/mm^2)	Elongation (%)
Specified value	≧1,373	—
Measured value	1,697	2

4.6 Properties of cable

The armored cable has annealed copper strand wire conductors insulated with polyethylene and armored with titanium alloy (Beta C) wires. Its construction is illustrated in **Fig. 6**, and its general view is given in **Photo 1**. Details of the cable are as reported by Murayama et al[1], and only brief descriptions are to follow. Four types, A to D shown in **Table 7**, were trially manufactured. The main differences between the four types are as follows. Type A is a four-conductor cable, Types B and C are concentric-lay conductor cables, and Type D is a single-conductor cable. Type B has a plastic cushion layer inserted between the inner and outer armor layers. When the four types were compared in terms of mechanical and electrical properties, Type D

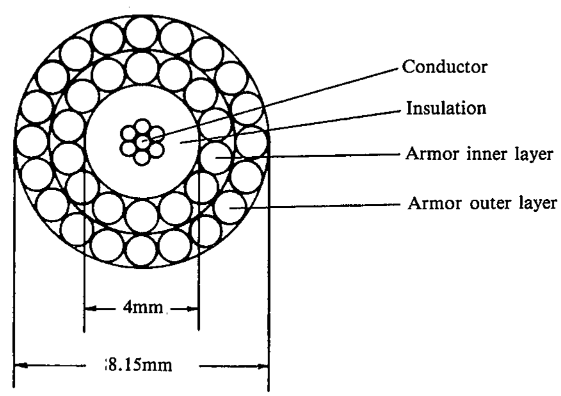


Fig. 6 Cross-sectional construction of deep-sea observation cable

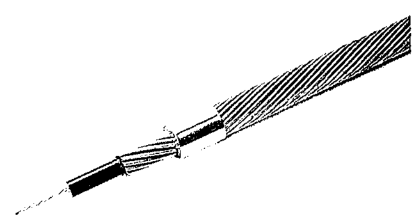
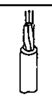
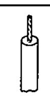


Photo 1 General view of deep-sea observation cable

Table 7 Construction and mechanical test results of prototype cables

Type			A	B	C	D
Cable construction	Cable conductors		 Four-conductor cable	 Concentric-lay cable	 Concentric-lay cable	 Single-conductor cable
	Armor	Inner layer	0.85mmϕ	0.75mmϕ	1.04mmϕ	1.04mmϕ
		Cushion layer	No	Yes	No	No
		Outer layer	0.65mmϕ	0.75mmϕ	1.04mmϕ	1.04mmϕ
Test results	Breaking load ($\times 10^3$ N)		28	28	39	35
	Number of twists to failure		4,700	5,200	6,000	4,300-6,800
	Cable rotation		—	−280°/ton·m	−94°/ton·m	—

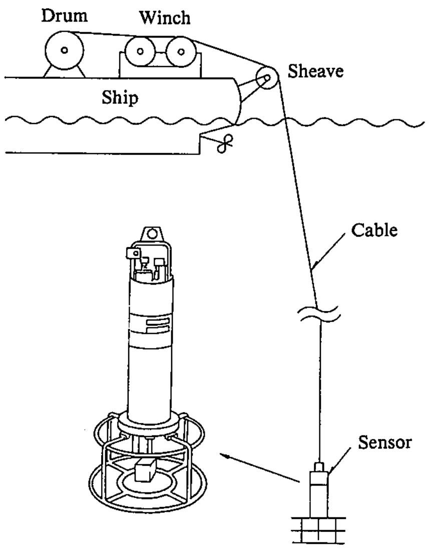


Fig. 7 Typical method of oceanographic observation

was found to be the best. Type D was thus selected as armored cable in the present project.

The properties of the armored cable thus produced are given in **Table 8**. Each item meets the design quality specified. Particularly, the breaking load is about 37 × 10^3 N and much greater than the target value of 32 × 10^3 N, and the number of twists to failure is about 5,200 and greater than the target value of 5,000.

Fig. 7 shows the oceanographic observation system where the armored cable was actually used on the oceanographic research ship "Hakuho Maru" of the Ocean Research Institute, University of Tokyo. An CTD (conductivity, temperature, and depth) measuring sensor is attached to the end of the armored cable and thrown into the sea to measure the conductivity, temperature, and depth of the water.

5. Conclusions

Titanium is ideal as armor material for marine cables, but has not been actually used in this application because of its fabrication difficulty. Recently, Furukawa Electric, Suzuki Metal Industry, and Nippon Steel jointly succeeded for the first time in the world in the manufacture of high-strength β titanium alloy wire and the fabrication of armored cable using the wire. It was reported that the world's first conductivity, temperature, and depth (CTD) measurements were successfully made by using the cable in the Challenger Deep, the deepest part of the Mariana Trench off the Philippines in December 1993[2].

The cable is expected to find widespread usage in the exploration of oil and other offshore resources and in the measurement of seismic tremors and geomagnetism, in addition to the initially intended oceanographic observation.

References

1) Murayama, Y. et al.: Furukawa Electric Review. (88), 119 (1991)
2) Taira, K.: "Ocean Flux" Newsletter. (8), 3 (1993)

Table 8 Construction, design properties, and measured properties of deep-sea observation cable

Item			Design quality	Measured value
Cable construction	Conductor (annealed copper wire strand)		0.45 mmϕ wire × 7	0.45 mmϕ wire × 7
	Armor (Beta C)	Inner layer	1.04 mmϕ wire × 14	1.04 mmϕ wire × 14
		Outer layer	1.04 mmϕ wire × 20	1.04 mmϕ wire × 20
	Outside diameter (mm)		7.90-8.40	8.39
Mechanical properties	Breaking load (× 10^3 N)		≧ 32	37
	Number of twists to failure		No failure to 5,000 twists under load of 14 × 10^3 N	5,200-5,400
	Rotation		≦ 150°/9,800 N·m	119°/N·m
	S bend		≧ 3,000 bends	No abnormality
	Water pressure resistance		≧ 11,770 N/mm^2	Acceptable
Electrical properties	Conductor resistance		≦ 17.0 Ω/km	15.8 Ω/km
	Insulation resistance		≧ 1 kmΩ·km	333kmΩ·km
	Dielectric strength		Resistance to 1,000 V DC for more than 1 min	Acceptable
	Armor resistance		≈ 74 Ω/km	70Ω/km