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New Technology for Manufacturing High-Quality Welded Titanium Tubes for Heat Exchangers

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Abstract:

With Nippon Steel's advance into the titanium business, a new welded titanium tube mill started commercial operation at the Hikari Works in July 1984. Since its startup, the mill has produced welded titanium tubes for heat exchangers and various other applications with its advanced manufacturing technology. It has three major features: (1) a perfect quality assurance system; (2) manufacturing technology incorporating latest techniques; and (3) a fully on-line manufacturing process. This paper describes the new technology developed for manufacturing welded titanium tubes, quality assurance system, and characteristics of tube products made at the mill .

1. Introduction

Titanium has excellent corrosion resistance under various environments compared with other metals, and has progressed as structural components of chemical reactors and vessels. Recently, titanium has come to be used in large quantities for steam turbine condensers at thermal and nuclear power plants and for heat transfer tubes of evaporation-type seawater desalination plants.

Nippon Steel's Hikari Works, long engaged in the manufacture of welded stainless steel tubes, started the production of welded titanium tubes in 1984 when the company entered the titanium business. Commercially pure titanium ingots of good quality are slabbed and hot rolled at another works of Nippon Steel, and after transportation to Hikari, they are cold rolled, vacuum annealed, and processed into welded titanium tubes for heat exchangers and other applications.

This article describes the manufacturing equipment, quality assurance system, and product characteristics of the welded titanium tube mill at the Hikari Works.

2. Features of Welded Titanium Tube Mill

2.1 Available size range and mill specifications

The Hikari welded titanium tube mill is designed for the manufacture of welded titanium tubes to existing specifications. Prior to the mill construction project, through investigation was made on the market situation, technical problems in the industry concerned, and matters retated to quality requirements. According to the findings obtained, a welded titanium tube mill of the latest design was engineered to supply the market with welded titanium tubes of the highest reliability for heat exchangers in the electric power industry. The available product size range from the mill is shown in **Fig. 1**, and the product types and applicable specifications in **Table 1**.

The tubemaking line employs forming technology to ensure close dimensional tolerances and welding technology to guarantee extremely high weld quality. The whole line is housed in a clean room within the mill building. The welded titanium tubes are annealed on-line in a high-purity inert gas atmosphere, and the finishing and inspection line includes a nondestructive inspection (NDI) apparatus to check the products piece by piece so that their quality can be fully warranted.

*1 Hikari Works

2.2 Characteristics of forming technology

2.2.1 Forming to close dimensional tolerances

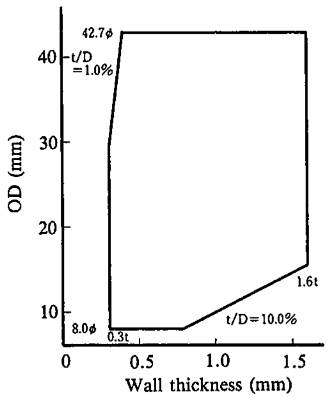

Fig. 1 Available size range

Table 1 Main product types and specifications

Product type	Specification
For heat exchangers	JIS H 4631, TTH28W to TTH49W
	ASTM B 338, Grade 1 to Grade 3
For piping	JIS H 4630, TTP28W to TTP49W JIS H 4635, TTP28PdW to TTP49PdW
	ASTM B 337, Grade 1 to Grade 3

The forming equipment was planned with a view to meeting close dimensional tolerances. **Fig. 2** shows the titanium tube TIG welding line, and **Fig. 3** the roll caliber map and product radius of curvature. Titanium is more difficult to form than carbon steel and stainless steel. Dedicated double-bend breakdown rolls are used to fully form the titanium skelp edges and prevent the edge buckling of light-gage titanium strip. The breakdown stands are followed by two fin pass forming stands. Four hydraulic roll stands are provided ahead of the welding machine to prevent the edge buckling or lapping of the skelp as much as possible before tungsten inert gas (TIG) welding. After the squeeze roll stands are installed four 2-roll sizer stands to meet close OD and roundness tolerances, and two light sizer stands to provide on-line straightening and to alleviate the tube straightening work load downstream.

2.2.2 High surface quality

When a titanium skelp is formed with tool steel rolls as done for welded stainless steel tubes, galling defects often occur on the titanium tube surface owing to the difference of peripheral speed between the titanium tube surface and the roll surface. The Hikari mill uses special copper alloy rolls to assure good surface quality. The copper alloy rolls are changed according to the cumulative rolling length.

2.3 Characteristics of welding technology

2.3.1 Welding environment

Since titanium has extremely high affinity for oxygen and

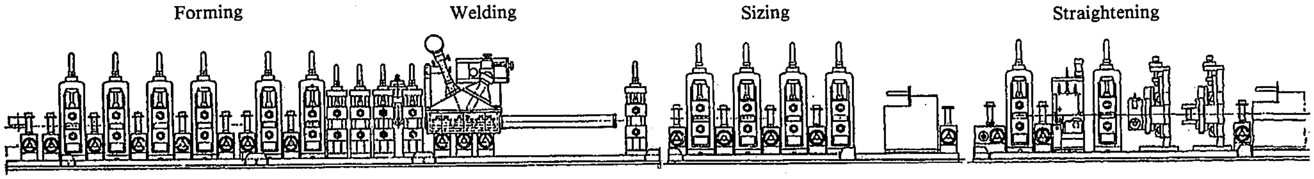

Fig. 2 Titanium TIG welding line

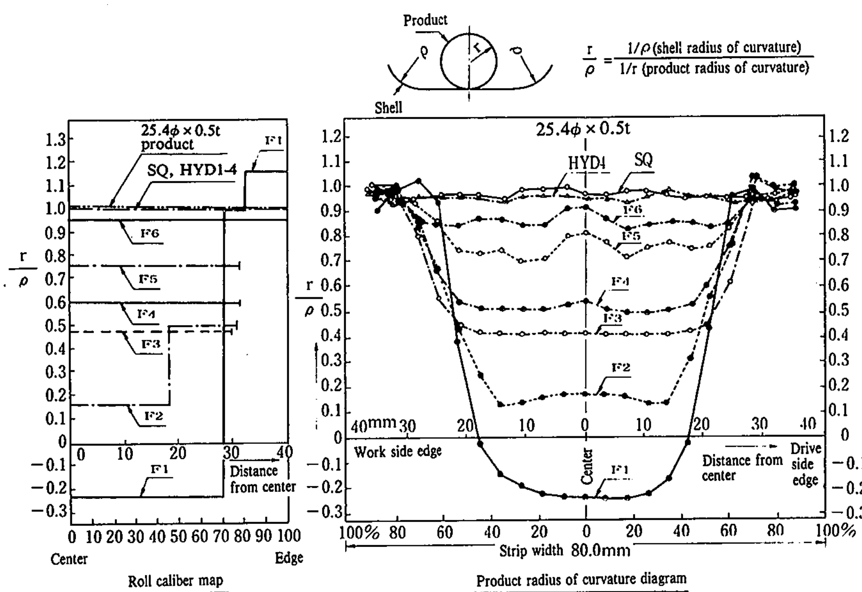

Fig. 3 Roll caliber map and product radius of curvature diagram

nitrogen, titanium should be welded in such an inert gas as argon. When the titanium skelp is poor in cleanliness, it develops many weld defects when welded. For example, weld defects result from titanium powder or oil and grease deposited on skelp edges in trace amounts and from dust and other foreign matters entering from the surroundings during forming and welding. To prevent the occurrence of such weld defects, skelp edge burrs are removed by the deburring unit, as shown in **Photo 1**. The skelp edges are also brushed and washed to assure good weld quality. Besides, the mill line section from uncoiling to welding is housed in a clean room to preclude the infiltration of dust and other foreign matters.

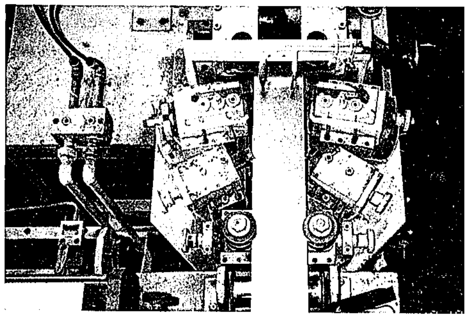

Photo 1 Deburring unit

2.3.2 Welding technology

The TIG welding process is adopted to weld titanium tubes. The Hikari mill adopts the high-pulse TIG welding process. With the high-pulse TIG welding process in which high-frequency pulses are superimposed on direct current, the rigidity, directivity, and concentration of the argon arc are substantially strengthened in the frequency region of 5 kHz and above. These factors combine in stabilizing the arc behavior relative to the base metal so that smooth weld beads can be obtained. **Fig. 4** shows the effect of the frequency on the arc pressure, and **Photo 2** the structure and shape of a TIG weld.

The mill has the welding electrode tilted forward in relation to the tubemaking direction and has the entire squeeze stand covered with a seal box and kept in an argon atmosphere, in order to raise productivity through high-seed welding operation while ensuring the desired weld quality. Typical welding conditions are presented in **Table 2.** The optimum ranges of welding conditions are determined according to the results of many plant experiments. Such examples are shown in **Figs. 5 and 6.**

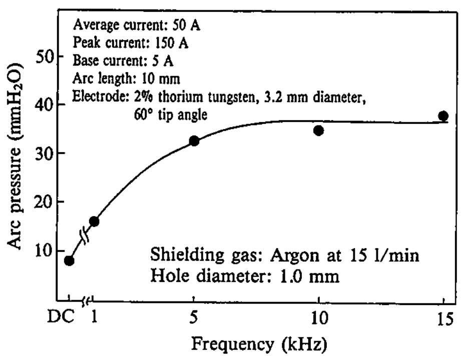

Fig. 4 Effect of frequency on arc pressure

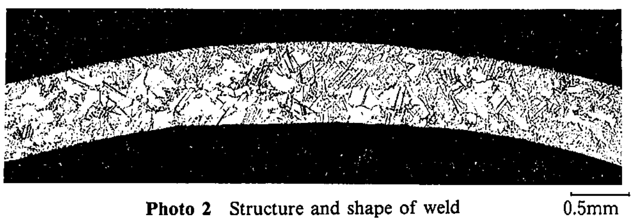

Photo 2 Structure and shape of weld

Table 2 Welding conditions (TTH35W, 31.75mmϕ × 0.5mmt)

Welding speed (m/min)	Total current (A)	High-pulse current (A)	Voltage (V)	Torch angle (°)	Electrode diameter (mm)	Electrode height (mm)	Torch gas (l/min)	Outside gas (l/min)	Inside gas (l/min)
5.5	220	95	10.0	35°	2.4	1.8	15	13	30

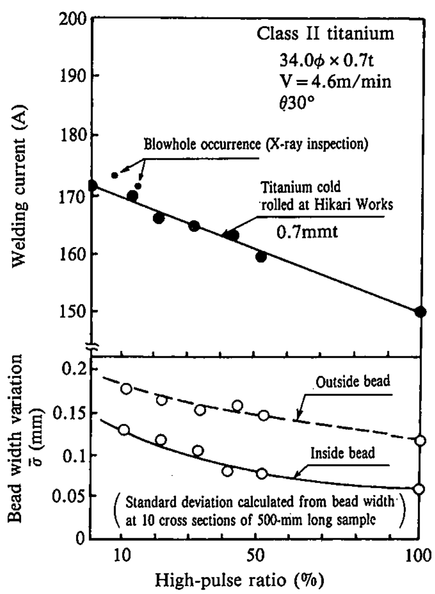

Fig. 5 Effects of high-pulse ratio on welding current and bead width

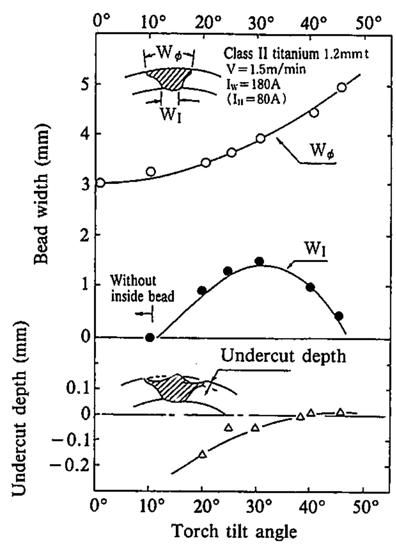

Fig. 6 Relationship of torch tilt angle with bead width and undercut depth

2.4 Characteristics of heat treating technology

As for heat treatment the mill is characteristic in that it is equipped for on-line annealing. When titanium tubes are heated to high temperatures of about 400°C or more, they are oxidized and colored. As described in ASTM B 338, welded titanium tubes must be annealed at a minimum temperature of 482°C (900°F). At the Hikari mill, the induction heating section and the subsequent cooling section are covered with cylindrical casings and maintained in an argon atmosphere. As a result, the welded titanium tubes are completely protected against oxidation to ensure clean surfaces. The atmospheric annealing temperature is measured by a radiation pyrometer and automatically recorded on charts so that the records can be verified by customers or third parties.

3. Features of Quality Assurance System

3.1 Traceability

Traceability is extremely important for the quality assurance of final products. This is the case particularly with welded titanium tubes for heat exchangers at nuclear power plants.

The Hikari welded titanium tube mill has two tubemaking lines. Each line is equipped with an automatic marking unit. The unit marks each piece of tube with not only the information specified in the applicable JIS and ASTM standards, but also the heat number, tube number and any other information required. The tube number marking, in particular, allows each tube to be individually controlled in such downstream steps as nondestructive inspection (NDI), pneumatic test, and final inspection.

The mill employs a package cross section drawing system as shown in **Fig. 7**. After the accepted tubes are packaged for shipment, their positions in the package can be identified to ensure perfect traceability.

3.2 Nondestructive inspection system

Welded titanium tubes for heat exchangers, the principal application field, are mostly designed to very small wall thicknesses from 0.5 to 0.7 mm, irrespective of the outside diameter. This makes it indispensable to eusure soundness around the circumference and along the length, including the weld metal as well as the base metal. The applicable JIS and ASTM standards specify eddy-current test (ET) or ultrasonic test (UT) as nondestructive test and hydrostatic test or pneumatic test (NT) as pressure test.

The quality assurance system of the Hikari mill conducts the ET and UT in the same step, followed by the NT, as shown in **Fig. 8**. It is characteristic in that it allows only those tubes that have cleared the nondestructive test and pneumatic test to be automatically sent to the next step. Rejected tubes are automatically ejected into reject cradles provided just after the nondestructive test and pneumatic test, respectively, so that they are not mixed with the accepted tubes.

4. Characteristics of Products

4.1 Dimensional accuracy

The dimensional accuracy of finished products demonstrates the high process capability of the mill as against the applicable JIS and ASTM standards. Some of the actual dimensional accuracy data are shown in **Figs. 9** to **17**. The products of the mill are controlled to excellent roundness. Tubes for heat exchangers in the electric power plant application are inserted into the tubesheet of condensers and are expanded so that each tube can be secured in the tubesheet with uniform circumferential force. In this consideration, product roundness is a very important quality factor. The Hikari welded titanium tube mill measures and controls the roundness of tubes at certain intervals, using roundness measuring instruments. The roundness measuring instruments are used also to determine the wear of the special copper alloy rolls for the tube forming and sizing operations.

4.2 Bead shape

Welded titanium tubes are sold with the bead left in the as-welded condition. Therefore, the outside bead in particular, must be smoothly connected along the outside profile. The shape of the outside bead, including undercuts, is known to depend on the angle of inclination of the TIG welding torch. The optimum

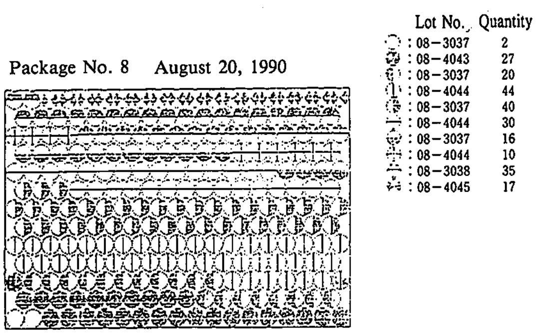

Fig. 7 Example of package cross section drawing (31.75mmϕ × 0.5mmt)

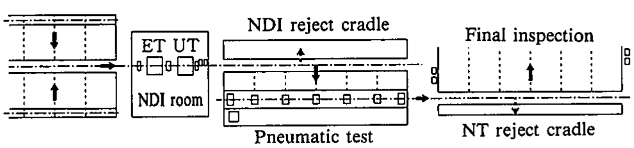

Fig. 8 NDI and pneumatic test process layout

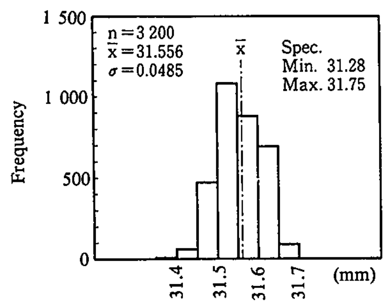

Fig. 9 OD accuracy (31.75mmϕ × 0.5mmt)

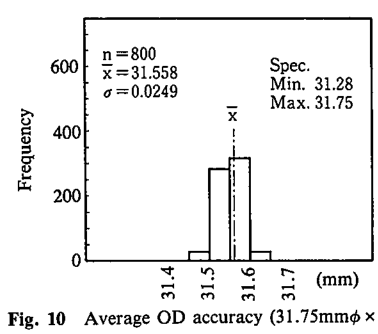

Fig. 10 Average OD accuracy (31.75mmϕ × 0.5mmt)

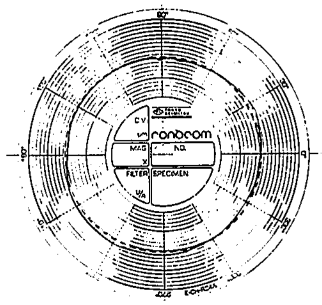

Fig. 11 Roundness chart (31.75mmϕ × 0.5mmt)

angle of inclination is established according to the results of plant test.

The shape of the inside bead, its height, in particular, is controlled by regulating the gas pressure on the inside wall of the tube, independently of welding heat input control. The inside and outside bead dimensions are controlled through the manufacturing process and therefore are always kept to very close tolerances, as shown in **Fig. 15**.

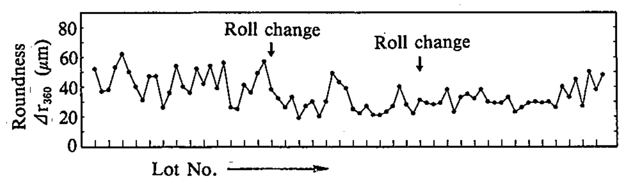

Fig. 12 Roundness variation during tubemaking (31.75mmϕ × 0.5mmt)

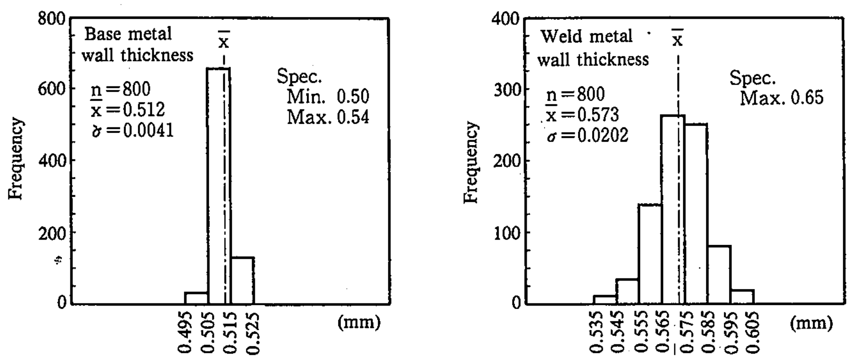

Fig. 13 Wall thickness accuracy (31.75mmϕ × 0.5mmt)

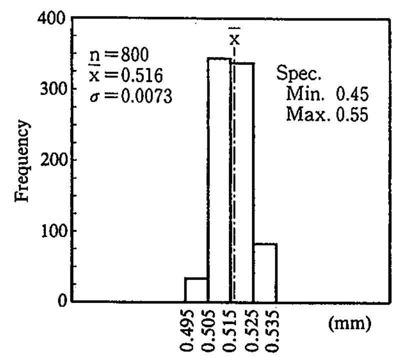

Fig. 14 Toe line wall thickness (31.75mmϕ × 0.5mmt)

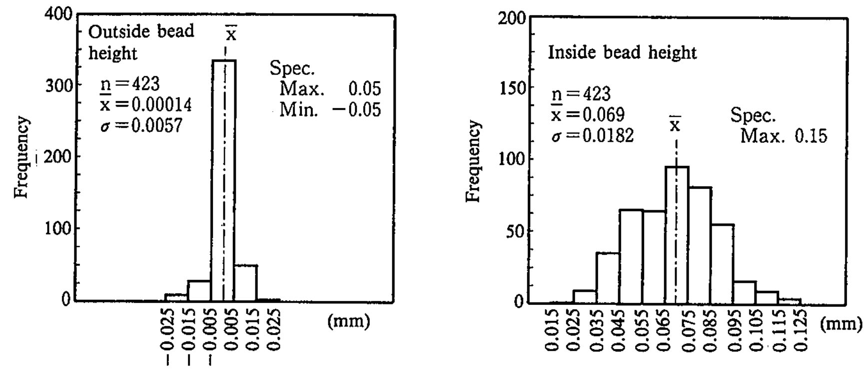

Fig. 15 Bead height (31.75mmϕ × 0.5mmt)

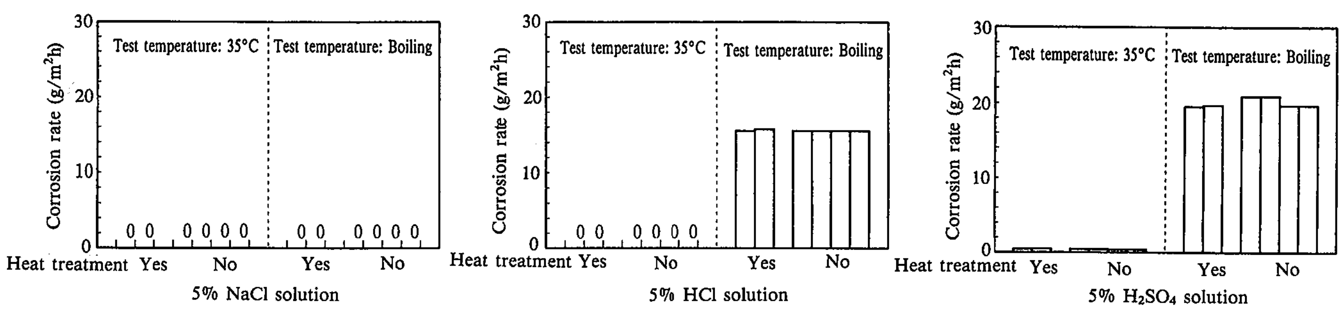

Fig. 16 Corrosion test results

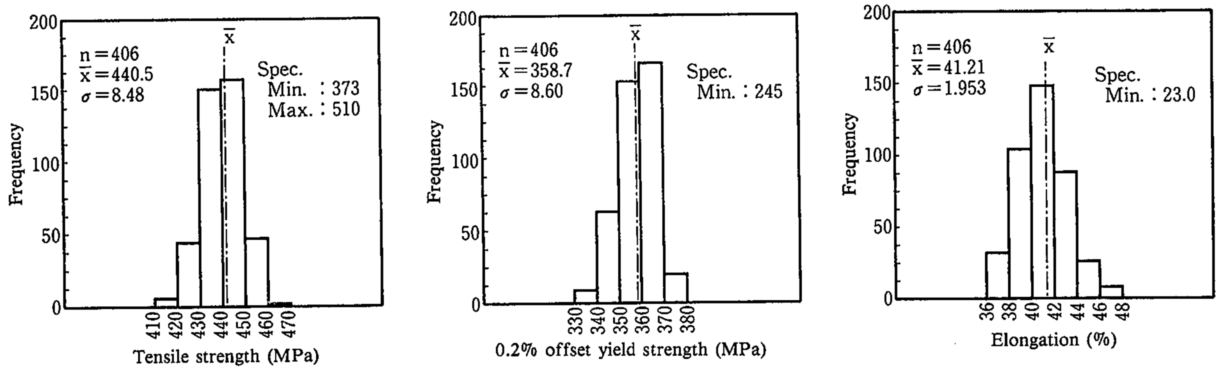

Fig. 17 Mechanical properties (TTH35W, 31.75mmφ × 0.5mmt)

5. Conclusions

Titanium came to be used as industrial material about 40 years ago and has since made steady progress in service performance in various industrial applications, thanks mainly to its excellent corrosion resistance. The Hikari welded titanium tube mill, since it was commissioned as part of Nippon Steel's titanium business, has worked hard to supply products of high performance and quality. Through the on-line operation of tube forming, finishing and inspecting processes with thoroughgoing quality control and with the aid of advanced automation technology, the mill has been smoothly operating as one of the latest mills since its startup in 1984.