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Development of Titanium Manufacturing Technologies and Applications in Titanium Business at Nippon Steel Corporation

Yasushi Murakami*1 Kazuo Sakai*1

Abstract:

In the 45-year history of the world's titanium industry, it has been full 10 years as of June, 1994 since Nippon Steel Corporation entered the titanium business. Taking this opportunity, titanium market trends are reviewed, and Nippon Steel's efforts to open up titanium application fields and develop titanium manufacturing technology are outlined. As to the company's market development activities, its basic policy, organization, implementation, and achievements in respective titanium application fields are introduced, and future directions are discussed. Regarding titanium manufacturing technologies, features of Nippon Steel's technologies are introduced process-wise, and measures taken for titanium quality assurance and cost reduction are presented together with future outlooks.

1. Introduction

It has been full 10 years since Nippon Steel Corporation stepped into the titanium business under its business diversification policy in 1984. Even since, the company has strived for producing high-quality titanium, developing new titanium products, and new titanium application technologies to open up new demand fields for titanium. As a result, Nippon Steel has caught up with its forerunners in titanium manufacture. The basic policy we set when we decided to engage in the titanium business was that we should not fight for a small piece of the pie, but should create new demand fields through the development of new products and new application technologies. The company is still expanding its titanium business according to the same basic policy.

Japan's annual shipment of wrought titanium marked a record 8,964 tons in 1990[1]. The world demand for titanium started to decline owing to dwindling arms production after the end of the Cold War and the worldwide business recession. On top of that, the collapse of the Soviet Union released surplus titanium sponge and semifinished titanium products to the free world, and the Japanese yen has rapidly appreciated against the U.S. dollar in recent years. These conditions have combined to make matters worse for Japan's titanium industry that exports a half of its titanium production abroad. Confident that this excellent material titanium is found to attract growing demand, the Titanium Study Group (TSG) Committee of the Japan Titanium Society predicts that the wrought titanium market will grow at least to 13,000 tons by the year 2001[2]. The greatest challenge for the titanium manufacturers is to develop new titanium applications and products appealing to customers and to timely supply them to customers at reasonable prices.

In the following, the efforts Nippon Steel has made in the past decade to establish titanium manufacturing technology and develop new applications for titanium are reviewed, and future outlooks for titanium are presented.

2. Trends in Titanium Demand

2.1 Titanium market and demand prediction

Besides its three largest features, namely, lightweight, strength and corrosion resistance, titanium has many other excellent properties as listed in **Table 1**[3]. The general public has come to

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*1 Titanium Div.

Table 1 Physical properties of commercially pure titanium

Melting point	1,668°C (slightly higher than iron)
Specific gravity	4.5 (about 60% of iron and about 1.7 times greater than aluminum)
Coefficient of thermal expansion	8.4×10^{-6}/°C (about a half of 18-8 stainless steel and one-third of aluminum)
Thermal conductivity	0.041 cal/cm^2/s/°C/cm (approximately the same as 18-8 stainless steel)
Electrical resistivity	55 Ω-cm (greater than pure metals except for 18-8 stainless steel)
Magnetic permeability	1.0001, which means that commercially pure titanium is nonmagnetic
Crystal structure	Close-packed hexagonal lattice and body-centered cubic lattice under and above transformation temperature (885°C), respectively
Young's modulus	10,850 kg/cm^2 (about a half of iron and about 1.5 times greater than aluminum)

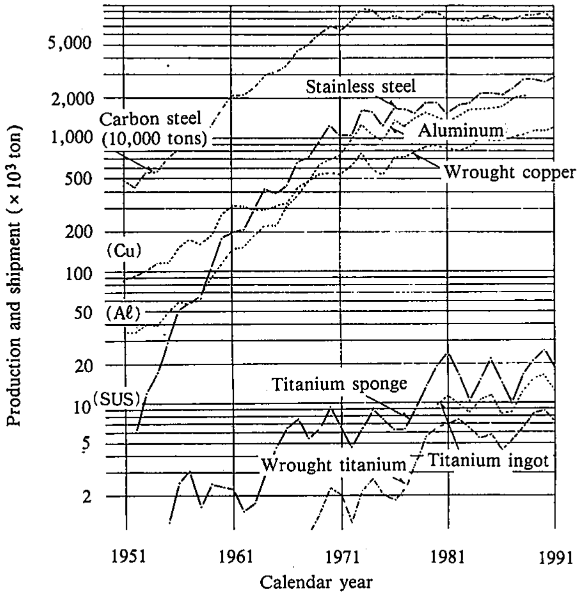

Fig. 1 Changes in production and shipment of titanium as compared with main rolled metals in Japan

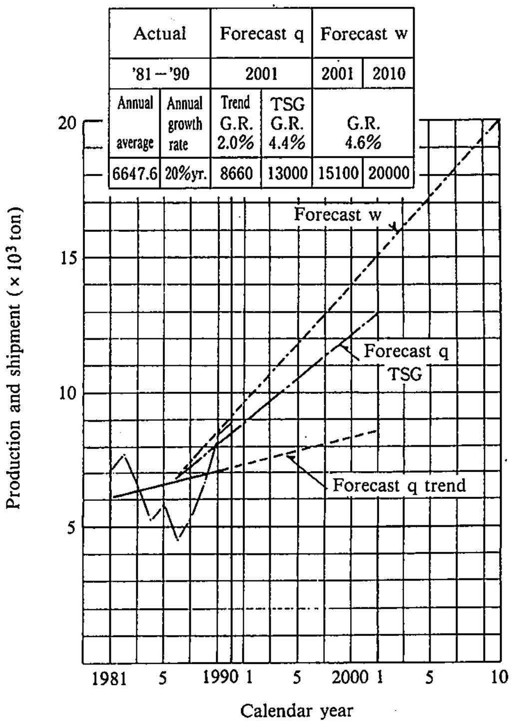

Fig. 2 Medium- and long-term demand forecasts for wrought titanium

recognize titanium as material of eye glasses and golf clubs, but not yet as an industrial material. Metallic titanium was commercially produced for the first time in the world when Du Pont of the United States began producing titanium sponge in 1948. Four years later in 1952, Osaka Titanium (present Sumitomo Sitix) started the commercial production of titanium sponge. The industrial-scale production of wrought titanium was began by Sumitomo Metals in 1954 and by Kobe Steel in 1956[4,5]. This was only about 40 years ago. In the United States, titanium alloys with high specific strength met growing demand for use in military and commercial aircraft. In Japan, commercially pure titanium found increasing demand in the chemical and electric power industries on the strength of its corrosion resistance. The industry has had many pioneers who strived to develop applications for titanium, as exemplified by titanium tubes in condensers of power plants, titanium tubes in sea water desalination plants for the Middle East, titanium electrodes in the caustic soda industry, and titanium sheets in plate-type heat exchangers.

Fig. 1 shows transitions in the production and shipment of main rolled metal products and titanium in Japan on a logarithmic plot[1]. Stainless steel and aluminum have increased at almost the same slope as carbon steel, but titanium has grown at a considerably milder slope. This low growth rate for titanium despite its excellent service performance is mainly because its extreme costliness limits its use to special fields and prevents its entry into general industrial fields and the consumer goods market. Although titanium has excellent service properties as noted above, it is difficult to bend, machine and weld, is prone to seizure, and is therefore shunned by fabricators. To expand the titanium market, the titanium price must be held at an affordably low level and technology must be advanced to facilitate the fabrication and application of titanium. Public relations activities should also be intensified to stress the service performance of titanium and to show that titanium is less costly than conventional materials when properly used. **Table 2** and **Fig. 2** show the medium- and long-term demand projections of wrought titanium[2], and **Fig. 3** the changes in the domestic shipment of wrought titanium by demand category. The titanium demand grew mainly in the chemical, electric power, and water distilling industries. Starting around 1988, titanium was used in civil engineering and construction projects (labeled "new" and darkened in **Fig. 3**). Since then, the demand for titanium rapidly grew in these new fields to meet the current trend toward maintenance-free operation (elimination of dangerous, dirty and demanding manual jobs), grade sophistication, and environmental protection. The TSG Committee predicts that the demand for titanium will drastically increase to reach 1,500 tons in the year 2001 in the civil engineering and construction areas. Another emerging titanium consuming industry is the automotive industry, which is expected to use at least 300 tons and a maximum of 6,000 tons of titanium if its price can be sharply

Table 2 Medium- and long-term demand forecasts for wrought titanium (ton/year)

Section	Calendar year	Actual			1992 Forecast	2001 Forecast	Remarks
		1989	1900	1991			
Shipment	USA *1	24,997	23,924	15,600	14,000		
	EC *2	5,000	5,000	4,500	4,000		
	Japan	8,469	8,964	7,317	7,000	13,000	
Free world total		38,466	37,888	27,417	25,000		
Domestic demand breakdown	Chemical industry	1,822	1,472	1,389	1,400	2,000	
	Electric power and water distillation	642	1,372	959	680	1,500	
	Aircraft	232	266	237	250	500	
	Distributors	529	455	536	550	700	
	Construction and civil engineering	78	76	141	200	1,500	*3
	Automobiles	14	39	90	100	300	*4
	Marine and energy	—	—	—	—	200	
	Consumer goods and others	149 348	173 318	223 316	250 470	600 700	
Domestic demand total		3,814	4,131	3,891	3,800	8,000	*5
Exports		4,655	4,833	3,426	3,200	5,000	
Total		8,469	8,964	7,317	7,000	13,000	*6

Remarks *1 US 1989 and 1991 actual results are from the Titanium Development Association, and 1992 figures are estimated by the secretariat of the Japan Titanium Society.

*2 EC figures are estimated by the secretariat of the Japan Titanium Society.

*3 – *6 Some committee members said that if titanium price is sharply reduced, its demand will increase to 3,000 and 6,000 tons per year in construction and civil engineering and automobile areas, respectively. In that case, the domestic demand total and the total demand will be 15,000 and 20,200 tons, respectively.

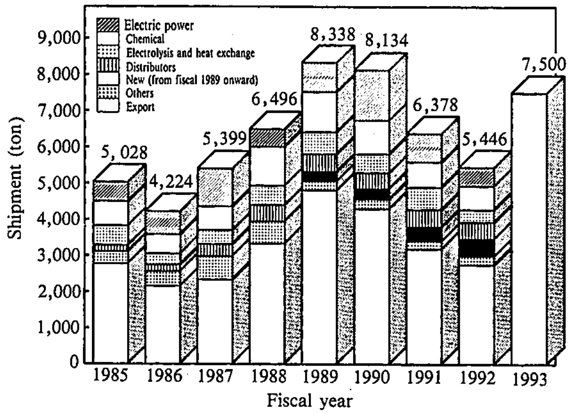

Fig. 3 Change in shipment of commercially pure titanium by application in Japan

reduced, in the year 2001. In September 1992, the U.S. government and the Big Three automakers announced that they would join forces to improve the fuel economy of automobiles by three times in 10 years[6]. Protection of the global environment increases the need for reducing the automobile weight, which in turn will increase the use of titanium. Titanium, which had been used only in racing cars, was adopted as material for the spring retainers of the Gallant GTX, a high-class limited-volume passenger car made by Mitsubishi Motors in 1989[7], and for the connecting rods of the sports car NSX of Honda Motor in 1990[8]. The shipment of titanium for automotive applications smoothly increased from 14 tons in 1989 to 90 tons in 1991. There is a great possibility that titanium will be adopted as a means of reducing the weight of structural parts like moving engine parts and as functional parts, such as door mirror vibrating plates (already available at buyer's option on Toyota's luxury cars) and pressure sensors[9]. According to the fourth survey report on the substitution of aluminum in automotive parts issued by the Japan Light Metal Association, the consumption of aluminum in 20 models of cars marketed in Japan in 1990 exceeded 100 kg per unit on the average[10]. If 1% of that aluminum consumption is replaced by titanium, it will translate into a new titanium market of 10,000 tons per year, which is of about the same scale as today's titanium market. The titanium connecting rods adopted in the Honda NSX weigh 470 g per piece and total 2.82 kg for six cylinders[8]. The present titanium market is that small. The excellent performance of titanium is already proven on racing cars, and titanium is beginning to be used in high-class limited-production cars. It is obvious that titanium will be used in large quantities if it price steeply falls. Development of technology for manufacturing automotive titanium alloys at low cost is as important as that of titanium fabrication technology (such as impartment of wear resistance) in opening up new applications for titanium.

2.2 Titanium manufacturing cost and sales price

Fig. 4 shows changes in the FOB export price of titanium sponge and wrought titanium[11]. Titanium prices skyrocketed to well over 5,000 yen per kg (5 million yen per ton) around 1981. This steep price rise caused users to shun titanium and triggered a decline in the titanium shipment (**Fig. 1**) as soon as the Japanese economy entered recession in 1983. In **Fig. 1**, the price of wrought titanium is the average price of all titanium products, the product mix widely varies from year to year, and the effect of foreign exchange fluctuation is also included. It is difficult to directly compare titanium export prices for different years, but a general trend can be known. The absence of such statistics makes it impossible to discuss domestic titanium prices, but 3-mm thick

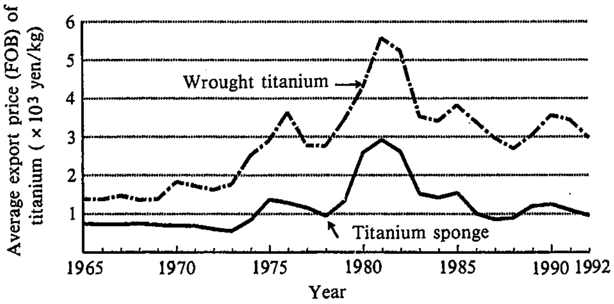

Fig. 4 Change in titanium price

titanium plates were said to sell at 3 million yen per ton in about 1970[12]. Despite some change with business cycles, the domestic titanium prices are not far from that level. Considering the commodity price increases in the past 20 years, the titanium price has significantly dropped. Most of the titanium sponge and wrought titanium manufactures are in the red or barely break even. The average price of 0.3-mm thick titanium sheets is now 3 million yen per ton[13]. Titanium is ten times as costly as stainless steel, but its specific gravity is 60% of that of stainless steel. Compared with stainless steel, thinner titanium gages can suffice as it can dispense with corrosion allowance, and it can last long free of maintenance. It can even be said that titanium is less expensive than stainless steel in some applications from the standpoint of life-cycle cost. Fluororesin-coated stainless steel roofing, the highest class of metal roofing to date, costs 15,500 yen per m^2 including installation cost against 35,000 yen for titanium roofing. When used for more than 25 years, the titanium roofing costs less than the stainless steel counterpart if the maintenance cost is counted in[2]. This advantage should be made known to customers. General people still think that titanium is expensive and shun it when the economy turns worse.

The titanium manufacturing cost is about 1 million yen per ton of sponge (400,000 yen for electric power and titanium oxide ore and 600,000 yen for smelting), 2 million yen for rolling into the thickness of 0.3 mm (including the ingot melting cost), and 1 million yen for fabrication into welded tubes[13]. For wrought titanium manufacturers, the ingot cost accounts for 40 to 45% of titanium sheet cost, and how cheaply to procure titanium ingots is a key point. Since the ingot cost is high, improving the yield is an effective cost-saving measure in the working process.

Titanium is generally produced in many types in small lots. Nippon Steel produces titanium on the same equipment as used for making steel, and therefore it takes about 6 months from ingot melting to product finishing. For this reason, production is stock production for the most part, which means poor width yield, generating open-order material. Many defects occur as the material passes through a complicated process, and the ingot-to-order yield is low at 70% or less on the average. Titanium shipment statistics by the Japan Titanium Society show that the wrought product-to-ingot ratio (yield) is 65% on the average. It is now an urgent issue to review the complicated process, build a more efficient production process, and improve yield in each production step.

3. Demand Development for Titanium

3.1 Commercially pure titanium

Nippon Steel's titanium business was originally designed to make effective use of steel production facilities. It started with the manufacture of commercially pure titanium, and now commercially produces almost all types of titanium products, including plates, hot-rolled sheets, cold-rolled sheets, welded tubes, bars, wire rods, and hot extruded products. It deserves special mention that engineers were assigned on the front-line of the demand development campaign. The front-line engineers gave detailed technical explanations to customers, answered questions from customers on the spot, relayed the customers' problems to research and production departments, and decided on the price and delivery lead time on the spot. This business practice has been officially recognized inside and outside the company.

The first target product in the demand developing campaign for titanium was welded tube for condensers of power plants, a field deemed certain to grow in the future. Condenser tubes were shifting from conventional aluminum brass tubes to titanium tubes for sea water leakage prevention. Japan's first entirely titanium-tubed condensers came on stream in 1980 or 4 years before Nippon Steel launched on its titanium business[14]. The company installed dedicated TIG welded titanium tube production lines at Hikari Works and started the manufacture of TIG welded titanium tubes for heat exchangers at chemical plant. These titanium tubes were then used for retubing condensers of local cooperative thermal power plants associated with Nippon Steel's works scattered over Japan, so that any problems with the titanium tubes used could be readily identified and solved to the benefit of establishing the company's TIG welded titanium tube manufacturing technology. Nippon Steel proved TIG welded titanium tubes in solely titanium-tubed condensers at the private power plant of Nagoya Works, and publicized the results to demonstrate the good quality of Nippon Steel's titanium tubes to the world's power companies. The company's titanium tubes were ordered in large quantities for the condensers of No. 3 and 4 thermal power plants in phase II of the Port Kelang project in Malaysia. To serve this large oversea project, a companywide project team was organized. Domestically, the company's TIG welded titanium tubes found use in various thermal power plants, and ultimately in nuclear power plants, the final goal of our challenge. Our welded titanium tubes have been adopted in 39 thermal power plants and 5 nuclear power plants to date. Their excellent quality was confirmed once again by our success in realizing export to China and Czechoslovakia—two hitherto untapped markets. Tubesheets are made by a production system established at the plate mill of Yawata Works, and are often supplied together with welded titanium tubes.

The second target was the titanium sheet field where high formability is required. Technology was completed to manufacture titanium sheets of good press formability thanks to the expertise acquired through sheet steel production. Nippon Steel's titanium sheets are highly rated as material for plate-type heat exchangers. They were used also in some outer panels (underparts of fenders and doors, for example) of the concept car TRI-X exhibited by Nissan Motor at the 29th Tokyo Motor Show in 1992[15]. The deep drawability of commercially pure titanium sheets made to close tolerances is superior to that of deep drawing quality steel sheets[16].

The third target are the civil engineering and construction area. Titanium was adopted as roofing material at the Hayasuhime Shrine of Oita Prefecture for the first time in Japan in 1973[17]. When Nippon Steel entered the titanium business, metal roofing materials were gaining popularity and advancing from high-grade color-coated steel to stainless steel. In water front and hot spring regions, even stainless steel roofs rusted, and titanium came into the spotlight as maintenance-free roofing material suited to such environments. Nippon Steel's titanium roofing was first used in the gymnasium of Maten Elementary School in Okinawa Prefecture, followed by the roof, big ridge cover panel and bargeboard of the main sanctuary building of the Sekai Mahikari Bunmei Kyodan, a contemporary religious group. The titanium roofing was used next in the retractable roof of the Fukuoka Daiei Dome that opened in 1993. Nippon Steel has increased the production of titanium roofing with the opening up of new markets in this way. Nowadays, many owners, designers, and contractors specify the use of titanium roofing. Research is under way in cooperation with a private research institution with the aim of theorizing the service performance of titanium roofing for buildings designated as national cultural properties. Under the influence of acid rain of late, copper roofs no longer produce aesthetic patina as in the past, but are blackened and eventually perforated. It will not be very long before copper is replaced by titanium as roofing material for important cultural properties in Japan. In the civil engineering sector, the low-cost titanium-clad steel plates originally developed by Nippon Steel were adopted for the first time in the world to provide corrosion protection for the steel bridge piers of the Trans-Tokyo Bay Highway now under construction[18,19]. This was an outcome of the efforts of Nippon Steel's project team that evaluated the corrosion resistance of titanium-clad steel plates, established the corrosion protection method using them, and developed the method of joining to steel piers. From the viewpoint of substantiating social capital while leaving no negative assets, titanium-clad steel plates are expected to find increasing use in marine civil engineering structures.

Demand for commercially pure titanium has been steadily growing also in the chemical and consumer goods fields, where, as elsewhere, the Nippon Steel brand is winning favorable evaluation from its users.

3.2 Titanium alloys

To advance into the aircraft industry, a large titanium consumer in the world, Nippon Steel introduced titanium alloy manufacturing technology from Titanium Metals Corporation (TIMET) of the United States and established technology mainly for titanium plate manufacture. The high quality of Nippon Steel's titanium alloy plates is now recognized by principal aircraft manufacturers in Japan and abroad. In parallel, we have developed our original technology to manufacture titanium alloy forgings, bars, and rods. The technology is best utilized in marine engineering. Nippon Steel's wrought titanium alloy (Ti-6Al-4V) was adopted in the pressure vessel of an unmanned submersible exploring unit that is designed to go down to the depth of 10,000 m below the sea level[20]. Nippon Steel also carried out the development of marine cables together with Suzuki Metal Industry and The Furukawa Electric Co., Ltd. at the request of Ocean Research Institute, University of Tokyo. In December 1992, the new titanium marine cables were installed on the ocean research ship "Hakuhomaru" and successfully used in collecting valuable data at a depth of more than 10,000 m in the world's deepest Mariana Trench[21].

The demand for titanium in the domestic aircraft industry is predicted to mark a mere 500 tons in the year 2001, as shown in **Table 2**. Unless titanium is domestically procured in large quantities in the joint development of the Boeing B777, for instance, no increase can be expected in the demand for titanium in this field of application. Now that its titanium manufacturing technology is recognized by the aircraft manufacturers who are most specific in quality requirements, Nippon Steel is endeavoring to reduce the production cost of titanium alloys in order to open up automotive and other new fields of application for them.

The automotive industry is believed to provide a big market for titanium alloys if their prices can be substantially reduced. Considering this, research is being deepened focusing on the reduction of manufacturing cost and development of application technology. The present research and development activities are centered on titanium alloy bars and rods, and many findings have already been obtained. One question relative to cost reduction is how to procure raw materials at low cost. Nippon Steel is the general agent in Japan of TIMET for titanium alloys and can enjoy the low-cost raw materials developed by TIMET. Another challenge is the development of low-cost working and finishing processes. Low-cost and easy-to-apply wear-resistant treatment technology has been practically completed and is now in the stage of long-term confirmatory plant test. Improvement and development of high-efficiency rolling technology, long-life super-finish technology, and dimensional accuracy and straightness enhancing technology are proceeding step by step.

3.3 Powder metallurgy

Nippon Steel noted the future potential of powder metallurgy for titanium, introduced the blended elemental process from Dynamet Technology Inc. of the United States in 1987, and pushed ahead with its original development to create a new market for titanium. Technology is established for producing near net shape parts without internal and surface defects by the CHIP process (combination of cold isostatic pressing or CIP and hot isostatic pressing or HIP), and some CHIP compacts are already commercially produced[22]. Elimination of HIP is challenged for further cost reduction, and technology is being developed for producing powder metallurgy parts comparable to forged parts in tensile strength, yield strength and fatigue strength[23,24]. Near net shape powder metallurgy can not only cut the secondary fabrication cost, but also form titanium-matrix composites that cannot be produced by ingot metallurgy. In this way, the weak points of wrought titanium are compensated for by best utilizing the features of powder metallurgy to expand the titanium business.

3.4 Intermetallic compounds

Concerning titanium aluminide intermetallic compounds, Nippon Steel is engaged in research on phase diagrams and alloy design as part of Japan's next-generation national project initiated in 1989[25]. Although titanium aluminide intermetallic compounds are still in the laboratory stage, Nippon Steel has completed its basic research and now watches market trends for titanium aluminide intermetallic compounds.

4. Development of Titanium Manufacturing Technology

Table 3 shows the types of wrought titanium products and the works where they are made. Nippon Steel purchases titanium ingots from Toho Titanium and makes almost all product types of commercially pure titanium. Since the titanium business was started to make effective use of the existing steelmaking facilities, titanium and titanium alloys are manufactured at four different works (five works initially). This is an extremely ineffi-

Table 3 Titanium product types and manufacturing facilities at Nippon Steel

	Slabbing and billeting (forging)	Hot rolling	Cold rolling	Tubemaking
Plates	Yawata (Japan Casting & Forging)	Yawata	—	—
Strip and sheets	Yawata (Japan Casting & Forging)	Hirohata	Hikari	—
Welded tubes	Yawata (Japan Casting & Forging)	Hirohata	Hikari	Hikari and associated company
Bars and wire rods	Kimitsu	Hikari	Associated company	—
Hot extrusions	Kimitsu	Hikari	Hikari	—

cient way compared with the company's integrated steel production system. Despite this handicap, each works has worked hard and established Nippon Steel's original titanium and titanium alloy manufacturing technology. In the following, features of the main production processes are introduced, and the future technological problems are outlined.

4.1 Ingots

Nippon Steel maintains close communication with Toho Titanium about the manufacture of ingots. Technical liaison meetings are periodically held to decide on detailed conditions as to impurities and surface defects. The two companies have an established cooperative arrangement for total cost reduction, under which research personnel are exchanged. As a result,the new titanium alloy TIX[26) was developed by effectively combining such impurity elements as iron, nitrogen, and oxygen. Work is now under way to develop a new series based on the TIX.

4.2 Rolling and finishing of slabs

Slabs for plates and sheets are rolled from ingots on the slabbing mill at Yawata Works. Ingots are produced in a cylindrical form by the consumable-electrode vacuum arc remelting (VAR) process. Ingots were initially forged into slabs at Japan Casting & Forging on a commissioned basis, but are now rolled into slabs from a cost-saving point of view. The maximum ingot diameter is 1,250 mm. For wider slabs, a plate mill broadsiding process is now under development. The slabbing of cylindrical titanium ingots is inferior in both workability and yield to square steel ingots. Various measures have been taken to improve yield, but any further yield improvement is a future challenge. Ingot size enlargement is now under study to improve yield in each step of manufacture. There is a limit to this ingot size enlargement, however. For, titanium is destined for the small-lot production of diverse product types, and any too large ingot size results in increasing open-order products in the downstream processes, which is uneconomical. Raw materials must be standardized by optimizing the number of chemical compositions and the ingot size, and technology must be developed for making many different types of titanium products from the limited number of slab sizes and types. Study is being made on the optimization of production process and slab size.

The oxidation-hardened layer, formed during slabbing causes surface defects in the next hot rolling step. It is therefore removed by wheel grinding in the slab conditioning stage. A wet grinding method was developed for this purpose[27) and has proved greatly effective in improving surface quality, extending the wheel life, enhancing efficiency, and preventing dust emission. There still remains a room for an improvement in hot rolling defects, however, and therefore the present slabbing conditions are reviewed with a view also to a slabbing cost reduction, and the present slab conditioning method is also reexamined.

Electron beam (EB) melting of titanium was formerly claimed to be unadvisable[28). Recently in the United States, however, it has been recognize to be an effective method of removing impurities from return scrap. Today, electron beam melting or plasma melting is specified as second-stage melting for titanium alloys for such quality-critical parts as aircraft frames and engine parts[29-31). In the United States, both the electron beam and plasma melting processes are commercialized for titanium, but in Japan only plasma melting furnaces are used on a production basis at Daido Steel[32). An electron beam melted 100% titanium scrap charge was cast into ingots, which were them rolled into slabs and subjected to evaluation for various rolling characteristics. The ingots are square, easy to handle in the soaking pit and slabbing mill, and conducive to yield improvement. If appropriate rolling reduction and annealing conditions are selected, hot-rolled plates and sheets can be directly produced from square ingots without slabbing. This procedure is effective in reducing the cost of the integrated rolling process. Evaluation is being made of the overall production cost including the melting cost.

4.3 Rolling and finishing of plates

Titanium plates are rolled on a stainless steel plate mill at Yawata Works. The plate mill can roll plates up to a width of 4,500 mm, a value comparable to that of the similar plate mill at NKK. Since the Yawata plate mill had only a small shape correcting capability, how to improve the shape of rolled plates was a problem. Young's modulus of titanium is about a half of that of steel. This means that roller flattening is limited in the capacity of correcting the distortion of rolled plates. Each plate producer has difficulty in flattening plate products, as exemplified by press flattening and creep flattening in the furnace with weighting. In April 1994, Nippon Steel introduced a vacuum creep flattener (VCF) for the first time in Japan. The VCF equipment is smoothly operating and has such an excellent flattening capability that it can guarantee wave steepness of 1 mm/m or less. The VCF was approved as a heat treating furnace by domestic aircraft manufacturers Mitsubishi Heavy Industries and Kawasaki Heavy Industries. We think that the flatness of Nippon Steel's titanium plate products, be they of commercially pure titanium or titanium alloy, is unparalleled in Japan. The VCF facility allows the minimum thickness of the widest plates to be reduced from 8 mm at present. The maximum width of 4.0 mm thick plates has been 2.0 m to date. Much wider plates of this thickness will become producible in the future. It is highly likely that the machining of plates, traditionally done to meet dimensional tolerances, may be eliminated or reduced. The absence of internal strains due to roller or press flattening helps suppress welding strains. Vacuum creep flattening is thus considered very beneficial to customers, too.

When the VCF was introduced, a wide grinding machine was installed to improve efficiency and surface quality. This has been made possible by the flatness improvement obtained with the VCF.

4.4 Hot rolling of sheets

Titanium strip is hot rolled on a latest hot strip mill at Hirohata Works[33]. When Nippon Steel entered the titanium business, hot-rolled titanium sheets were also produced at Muroran Works, but when the Muroran hot strip mill was shut down in 1991, the hot rolling of titanium sheets was concentrated at Hirohata Works. The finishing stands of the Hirohata hot strip mill are all of the pair cross type and have excellent flatness control capability. There occur so many types of defects in the hot rolling process that it is difficult to identify their causes and take appropriate countermeasures to them. Descaling is performed on a hot annealing and pickling (HAP) line at Hikari Works. Hot rolling defects not removable by descaling were removed on a coil grinder line. This grinding operation is a significant cost increasing factor, and its elimination was an important issue until very recently. First, hot rolling defects had to be prevented from occurring. A working group was formed with the participation of research staff to identify causes and establish countermeasures. The causes of specific defects were pinpointed by detailed analysis of hot-rolled strip surfaces and thoroughgoing observation of the hot rolling process, and countermeasures thus established were steadily put to practice. The strip processing conditions on the HAP line were reviewed and optimized. As a result of these efforts, almost all hot coils can now be sent without retouching to the next cold rolling process. This makes a sharp contrast with the prior practice of grinding almost all hot coils to remove surface defects. Raising this non-retouching ratio to 100% is a challenge facing the slabbing and hot rolling processes.

4.5 Cold rolling of sheets

Titanium strip is cold rolled on a 20-high Sendzimir mill for stainless steel at Hikari Works. The oxidation-hardened layer formed during hot rolling and the work-hardened layer produced by the coil grinder to remove defects heavily influence the occurrence of defects during cold rolling. It is important that these hardened layers should be completely removed on the pickling line. The hot coils are pickled on the HAP line comprising annealing, shot blasting and nitric-hydrofluoric acid pickling. After a thorough review of respective operating conditions, hot coils with very beautiful surface finish can now be supplied to the cold rolling step. Titanium is considerably inferior to rimmed steel in cold workability. Titanium is approximately equal to stainless steel in constrained deformation resistance[34], but is liable to seizure on work rolls. It is therefore important to minimize the heat generated during rolling. To reduce the rolling load, hot coils are cold rolled on a Sendzimir mill with 50 to 80 mm diameter work rolls, at a low speed, and with light reduction per pass, but productivity is pretty low. Rolling on a more efficient tandem mill with larger work rolls is under study to prepare for a drastic increase of production in the future. There still remain many problems to be solved, including such surface defects as seizure and oil pits, strip threading and off-gauge problems.

Cold-rolled strip is annealed in a batch-type vacuum annealing furnace. Flatness-critical sheets are temper rolled on a six-high skinpass mill and flattened on a tension leveler. Some cold-rolled strip products for architectural and electrode applications are required to have pickled surface. The optimum process to meet this requirement is being studied, with cost factor taken into consideration.

4.6 Manufacture of welded tubes

Two new TIG units were installed to make welded titanium tubes of the highest possible quality. Welded tubes for power plants must meet very severe quality requirements. To secure such high quality in welded tubes, the welding speed was limited to 3.5 m/min for the standard tube size of 0.5 mm wall and 25 mm outside diameter. Therefore, Nippon Steel's welded tube manufacturing cost was considerably high, and its reduction was one of the most critical issues very recently. Much effort has been expended to raise the welding speed for the purpose of drastically cutting the tubemaking cost. The welding speed has been successfully raised to a maximum of 8 m/min by minimizing the strip edge burrs, improving the washing method, reviewing the welding conditions, and improving the forming roll material. In the finishing process, the pneumatic test bottleneck was eliminated by increasing the capacity of pneumatic testing equipment. The unit now finishes welded tubes at an average speed of 6 m/min. The resultant increase of productivity has doubled the monthly processing capacity and lowered the tubemaking cost to the level prevailing in the industry. Welded tubes for general applications except for power plants should ideally be supplied at a price befitting the quality required in specific applications in order to prevent the cost increase accompanying over-specification. To have discussions with customers is always necessary in this point. Efforts will be continued for reducing the cost of welded titanium tube production.

4.7 Rolling of bars and wire rods

Billets for bars and wire rods, including those for hot extrusion, are rolled on blooming and billeting mills at Kimitsu Works and are sent to Hikari Works. The wire rod mill of Hikari Works is a mass-production high-speed mill and features a final rolling speed of 90 m/s for 5.5 mm diameter. Small-lot production is impractical on this high-speed mill, and therefore orders are assembled and rolled in a larger lot. Mill modifications have been made for titanium bar rolling, and various more measures will become necessary in the future. When induction heating was tested on titanium alloys, for example, short-time atmosphere induction heating proved effective in suppressing the formation of oxidation-hardened layer and very useful in reducing rolling defects. Other cost-saving measures are also undertaken, including improving dimensional accuracy, establishing super-finish technology (such as tool life extension), and developing small-diameter bar straightening technology. Nippon Steel's wire rod shipment is small. Wire rod cannot be ignored when developing a new market for titanium. Establishment of low-cost bar and wire rod manufacturing technology is one of our most important challenges in the future.

5. Conclusions

This special issue features the representative application development, manufacturing technology development, and research and development work Nippon Steel has carried out since it first launched on its titanium business. Concerning titanium and titanium alloys as well as titanium aluminide, Nippon Steel has published 286 papers (breakdown shown in **Table 4**), made 227 patent applications (those published up to 1992), and acquired 28 patents in the past decade.

After quality building and application development with top priority, Nippon Steel has achieved the shipment of titanium and titanium alloys as recognized in the industry. To meet the commitment as part of Nippon Steel's diversified management, those engaged in the titanium business are working to change to profita-

Table 4 Papers published by Nippon Steel on commercially pure titanium and titanium alloys

	Process	Metallurgy	Surface and interface	Secondary fabrication	Product development	Total
Commercially pure titanium	8	23	24	4	4	63
Titanium alloys	10	117	7	9	7	150
Titanium-clad steel plates	10		20			29
Powder metallurgy	1	6			2	9
Titanium aluminide	7	27				34
Total	36	173	51	13	13	286

bility with top priority given to cost reduction. It is urgent to accomplish dramatic cost savings to develop new markets and supply at affordable prices to customers.

Nippon Steel's titanium business has grown in a short time thanks to the patronage of customers and guidance and encouragement by all those concerned. We have learned much through joint work at development meetings and through technical exchange at technical committee meetings with member companies in the Japan Titanium Society. Our technical level has been enhanced through active discussions with university professors and researchers from public research institutes and private companies at meetings organized by such academic societies as the Iron and Steel Institute of Japan and the Japan Institute of Metals.

For the Japanese titanium industry to grow further, it is extremely important that titanium manufacturers should work hard together in upgrading their technical levels. We will conduct positive technical exchange with all those concerned and endeavor to contribute to the development of Japan's titanium industry under their guidance and encouragement.

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