UDC 669 . 295 . 5

Technical Review

Manufacturing Technologies for Products of Titanium and Its Alloys

Kinichi KIMURA* Toshinori KATAYAMA

Abstract

Newly born "Nippon Steel & Sumitomo Metal Corporation" has taken over high-level technologies on titanium, which have long been cultivated in each company, Nippon Steel Corporation and Sumitomo Metals Industries, Ltd. Moreover, by effectively combining both technologies, Nippon Steel & Sumitomo Metal is now manufacturing and supplying highest quality commercial pure titanium products of quite wide range of size, and Nippon Steel & Sumitomo Metal is also manufacturing titanium and its alloys for aircraft industries, which demand quite high quality, including airframes and engine parts for which what is called premium grade is required.

1. Introduction

Nippon Steel Corporation and Sumitomo Metal Industries, Ltd. merged to form Nippon Steel & Sumitomo Metal Corporation in October 2012. This led to the former companies' products of titanium and its alloys (hereinafter "titanium" may also cover its alloys) being shipped from four factories of the new company, namely, Hikari Works (Yamaguchi Prefecture), Yawata Works (Fukuoka Prefecture), Naoetsu Works (Niigata Prefecture), and Osaka Steel Works (Osaka Prefecture). The first two factories had belonged to Nippon Steel, the last two to Sumitomo Metal. Field production at the factories is supported by the R&D activities of Research & Engineering Center (Chiba Prefecture, formerly of Nippon Steel) and Amagasaki R&D Center (Osaka Prefecture, formerly of Sumitomo Metal). This paper discusses manufacturing and R&D activities for titanium products of Nippon Steel & Sumitomo Metal after the merger.

2. History of the Titanium Business of Nippon Steel & Sumitomo Metal before and after the Merger

In 1952, six years after William J. Kroll succeeded in industrially producing titanium using the magnesium reduction method, Osaka Titanium, one of the then-Sumitomo Metal family companies, started trial production of sponge titanium. The company began commercial production in 1954. Then in 1968, separately from this, Sumitomo Metal began cold rolling of titanium sheets at Naoetsu Works.

The former Nippon Steel entered into the titanium business in 1984, 16 years after the titanium cold rolling at Naoetsu.

Before the merger, cold-rolled sheets of commercially pure (CP) titanium were produced mainly at Naoetsu. The factories received accreditation from aircraft builders within and outside Japan for cold-rolled CP titanium sheets for general industrial use as well as for aircraft use, for which high quality and strict quality control systems are required. Presently, Naoetsu Works is responsible for most of the cold-rolled titanium sheets that those aircraft builders use.

At Osaka Steel Works of the former Sumitomo Metal, equipment for producing titanium alloys was installed in 1984, and the factory obtained product accreditation from various aircraft-related heavy machinery builders in Japan and abroad in the following years, and ever since then it has produced and shipped titanium alloys for application to aircraft engine fan blades, for which a very high quality level is required.

On another front, the facilities of the former Nippon Steel produced cold-rolled sheets, and welded tubes and wire rods of titanium, at Hikari Works and plates at the Yawata Plate Mill Plant of Nippon Steel & Sumikin Stainless Steel Corporation; most of these were of CP titanium for general industrial use.

3. Demand for Titanium Products; Present Production Capacity

Figure 1 shows changes in the shipment of rolled titanium products in Japan over the years. The shipment amount in 2011 was 19,000 t (all units herein are metric), nearly four times that in 1984 (roughly 5,000 t), when the former Sumitomo Metal entered this in-

* Senior Manager, Head of Dept., Titanium Technology & Quality Management Dept., Titanium Technology Div., Titanium & Specialty Stainless Steel Unit
2-6-1 Marunouchi, Chiyoda-ku, Tokyo 100-8071

dustrial sector. **Figure 2** gives a breakdown of titanium product shipments in Japan in 2011, by consumer industrial sector.

Titanium has excellent resistance to corrosion, especially corrosion by salt water, and as such it is used in quantities for plate heat exchangers (PHEs), thermal power plant steam condensers, and other heat exchangers exposed to sea water; no less than 6,000 t of titanium was used in 2011 in Japan for a single desalination plant. After the disastrous earthquake in East Japan in March 2011, however, nuclear power plant construction has been suspended in the country, and in addition, the global economy has slumped owing to such reasons as European financial problems, and as a result, the shipment of rolled titanium products in Japan in 2012 was as low as roughly 12,000 t. Most titanium products consumed in Japan are of CP titanium; those for aircraft application account for only about 5%. Worldwide, however, the aircraft industry consumes nearly half of all titanium products, mostly titanium alloys. The aircraft industry is expected to grow further and consume more titanium per unit, and other industries in general are also expected to use more titanium as market conditions improve.

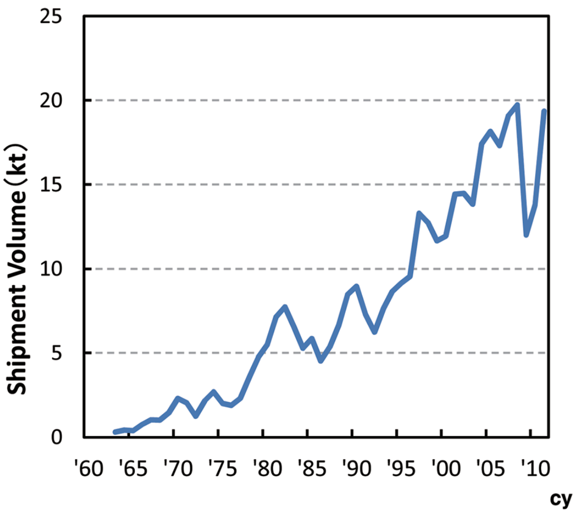

Fig. 1 Changes in the shipment of titanium products in Japan over the years

The two companies merged to form Nippon Steel & Sumitomo Metal in order to enjoy mutual complementarity in the steel market. This is the case also in the titanium field: whereas the former Sumitomo Metal had produced and supplied high-end products of titanium and its alloys for aircraft application (in addition to CP titanium products for general industrial use), the former Nippon Steel produced mainly CP titanium sheets for general industrial use. To better achieve the excellent corrosion resistance of titanium, thinner and thinner sheets are required, and the latter company held a leading position in the market of large-width, thin-gauge sheets; it also manufactured titanium tubes and wire rods.

To make the most of the expertise of the former companies, the new company focuses its R&D efforts on the development of titanium alloys, the use of which is expected to grow significantly for aircraft applications, as well as CP titanium products for general industrial use.

4. Manufacturing Technology

4.1 Production facilities

Figure 3 shows shipments of different kinds of titanium products in Japan in 2011. Flat products, namely thin sheets and heavy plates, account for approximately 70% of the total. Nippon Steel & Sumitomo Metal manufactures substantially all of the variety of titanium products: flat products, welded tubes, bars and forgings. Most of these products are manufactured at production facilities for steel. Because of the wide variety of titanium products, which include sheets, plates, tubes, wire rods and bars, the Nagoya and Hirohata Works (in Aichi and Hyogo Prefectures, respectively) are involved in their manufacture, in addition to the Naoetsu, Osaka, Hikari and Yawata Plate Mill plants mentioned earlier; thus the number of the company's works/plants involved in titanium manufacturing is six.

Nippon Steel & Sumitomo Metal is one of the world's first class integrated producers of titanium products; its in-house manufacturing processes extend from ingot casting to the final finishing of virtually all of the variety of titanium products, using manufacturing equipment that includes an electron-beam (EB) melting furnace, a breakdown rolling mill, forging presses, hot and cold rolling mills

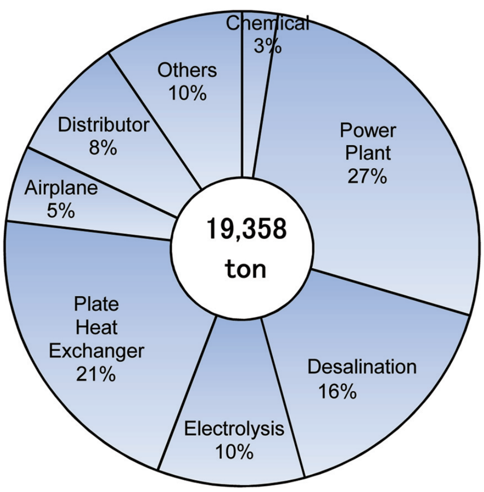

Fig. 2 Shipment of titanium products for different applications in Japan, 2011

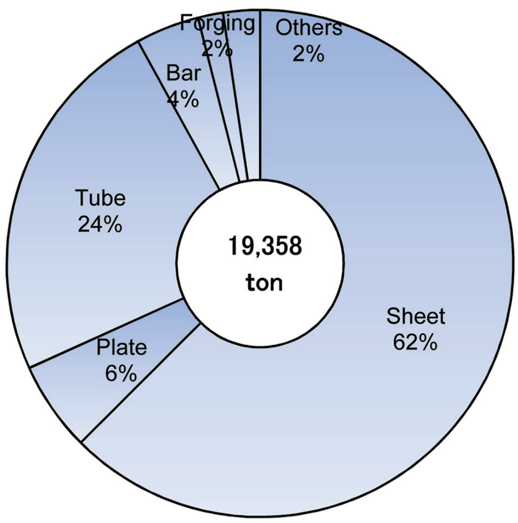

Fig. 3 Shipment of different kinds of titanium products in Japan, 2011

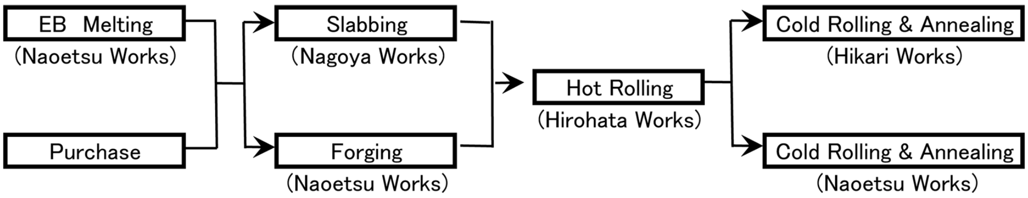

Fig. 4 Manufacturing processes of sheet products

for sheet products, plate rolling mills, a tube production line for welded tubes, and rolling mills for bars and wire-rods.

4.2 Raw materials

Titanium is the fourth most abundant metal element in the earth's crust. In Japan, Toho Titanium Co., Ltd. and Osaka Titanium Technologies Co., Ltd. produce titanium ingots by reducing titanium ore into metallic titanium, called sponge titanium, and then melting sponge titanium in EB melting furnaces or consumable-electrode type vacuum arc remelting (VAR) furnaces. These companies produce the world's highest quality of titanium ingots, and are the principal suppliers of sponge titanium and ingots for Nippon Steel & Sumitomo Metal.

To effectively reuse scrap titanium arising from in-house manufacturing processes, a new type of EB melting furnace was installed at Naoetsu Works in 2012. The furnace can melt lump scraps that conventional VAR furnaces cannot deal with, and is expected to play an important role in expanding the recycling of scraps that arise in different shapes and sizes. The EB melting furnace incorporates the company's accumulated technology and expertise in the melting, refining and solidification of titanium, and, among other technologies, thermal-liquid analysis technology employing numerical simulation.

4.3 Sheets

Figure 4 shows manufacturing processes for thin sheet products. Slabs are produced from ingots through either breakdown rolling at Nagoya Works or forging at Naoetsu Works, and then the slabs are hot rolled into coils at Hirohata Works. The hot-rolled coils undergo cold rolling, annealing and finishing at either Naoetsu or Hikari. Naoetsu forges slabs at high yields thanks to the forging pass schedule based on long experience and forming simulations. The breakdown mill of Nagoya Works is capable of efficiently rolling ingots that are as large as 20 t in unit weight into 250-mm thick slabs, in one heat.

The slabs are hot rolled through the hot strip mill of Hirohata Works. This mill, although rather compact for a hot strip mill, was designed to precisely control the width and lateral thickness difference (strip crown) of steel strips using a vertical roughing stand and finishing rolling stands of pair-cross-roll configuration; these features are effective also at producing titanium sheets of excellent accuracy in width and thickness. The hot bands thus produced are descaled, cold rolled and annealed into final sheet products at Naoetsu and Hikari.

Owing to their excellent corrosion resistance, CP titanium sheets are used in heat exchangers and other applications requiring corrosion resistance, and thinner and wider cold-rolled sheets are in demand in these application fields. Nippon Steel & Sumitomo Metal produces titanium sheets 0.3 mm or more in thickness and 1,524 mm or less in width. The relationship between the thickness and width of available products is given in **Fig. 5**: with Classes 1 and 2 CP titanium under JIS (equivalent to ASTM Grs. 1 and 2, respectively), the maximum width of cold-rolled sheets is 1,219 mm when

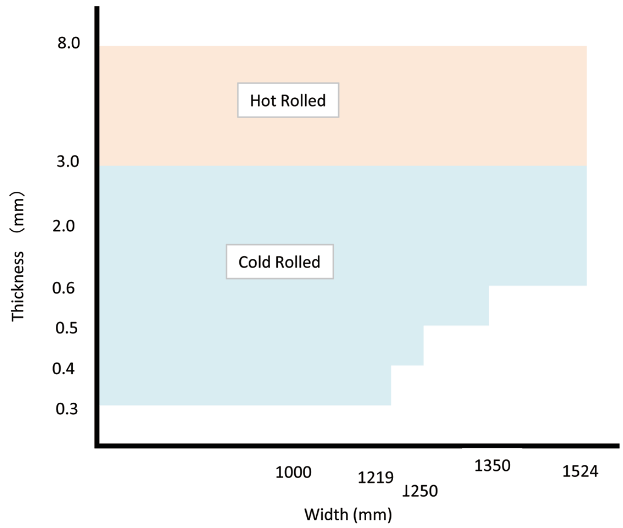

Fig. 5 Available size of sheet (hot and cold rolled products) JIS Class 1&2 CP titanium

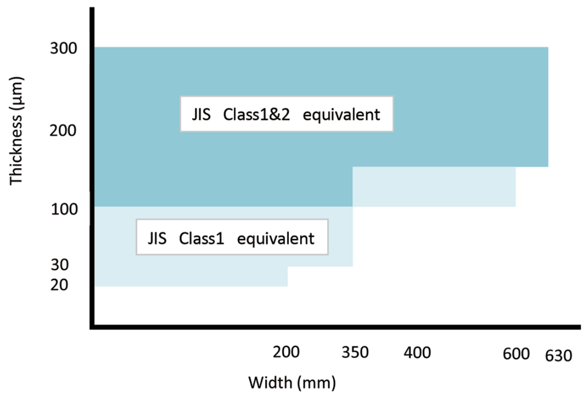

Fig. 6 Available size of thin foil (JIS Class 1&2 CP titanium)

the thickness is 0.3 mm, and 1,524 mm when the thickness is 0.6 mm; this size range is one of the broadest in the world. Tests are underway at the works to further expand the size range.

Naoetsu Works also produces titanium foils; the minimum thickness for the material equivalent to JIS Class 1 is 20 μm. The maximum width is 630 mm when sheet thickness is 0.1 mm (see **Fig. 6**). All of the mills mentioned above have obtained ISO 9001 and JIS Q 9100 certifications for their quality management systems for aerospace applications, and a special process certification from the National Aerospace and Defense Contractors Accreditation Program (Nadcap). In addition, as explained in Section 2, in appreciation of the excellent product quality and the quality management system, Naoetsu Works has obtained accreditation from aircraft builders, and supplies a considerable part of the cold-rolled CP titanium sheets that they use.

To reduce manufacturing costs, R&D activities have focused on process simplification and minimization of surface defects at hot rolling, which are carried over to cold-rolled sheets. More specifically, hot-rolling defect mechanisms have been metallurgically studied, and the effect of ingot surface conditioning, slab grinding and hot rolling conditions on the occurrence of defects have been made clear. Additionally, the company has developed technology to make slabs by forging and, jointly with Toho Titanium, to eliminate breakdown rolling of ingots into slabs. It has applied these technologies, succeeded in casting slabs directly from molten metal tapped from the EB melting furnace (the slabs being called DC Slab™), and produced sheet products from as-cast slabs through hot rolling, cold rolling and annealing. This was the world's first case of commercial production of cold-rolled titanium sheets from directly cast slabs without forging or breakdown rolling.

PHEs account for the largest part of the use of CP titanium sheets, and press formability is important for this use. Nippon Steel & Sumitomo Metal designs the material chemistry, and takes every quality control measure during cold rolling and annealing to produce homogeneous sheet products of high strength and formability to satisfy customer requirements.

The company has developed sheet products for external finishing of building roofs and walls, and has cultivated this market. Good surface appearance is important for this use, and to respond to building design requirements a wide variety of surface finishing is made available, including dull-finished sheets which are skin-pass rolled using shot-blasted work rolls, and color sheets treated with alumina blasting and anodizing.

In the late 1990s there were cases where the surfaces of titanium sheets used for building roofs and walls discolored after years of exposure to the environment. Nippon Steel & Sumitomo Metal looked into the cause of the problem and, for the first time in the world, established measures to prevent discoloration. Based on those measures, the company now offers titanium sheets highly resistant to discoloration. (See another article in this issue for more details.) Thanks to these efforts, the company presently holds a very large share of the building finishing market: it has supplied roughly 1,700 t of titanium sheets for the roofs and walls of a total of 570 buildings.

The titanium product lineup of Nippon Steel & Sumitomo Metal includes the Super-TIX™ series alloys. (For more details on these alloys, which the company developed on its own, see yet another article in the present issue.) Of these alloys, sheets of Super-TIX™ 51AF (Ti-5Al-1Fe) are produced in coils, despite difficulties intrinsic to this kind of high-strength $\alpha+\beta$ type alloy; the alloy is used for golf club shafts, to the satisfaction of many golfers. Cold-rolled sheets of another alloy in the series, Super-TIX™ 800, have a strength of 700 to 800 MPa, and are used for applications such as stab resistance for police officer protection. Thanks to their attractive appearance and light weight, the following alloys have found applications in automotive exhaust systems, where weight reduction and higher fuel efficiency are in demand: Super-TIX™ 10CU (Ti-1.0Cu) and Super-TIX™ 10CUNB (Ti-1.0Cu-0.5Nb), used for mufflers and other parts of motorcycles and automobiles.

4.4 Plates

Slabs for plate products are produced in the same manner as those for thin sheets, at Naoetsu by the forging of ingots, and at Nagoya by breakdown rolling of ingots (see **Fig. 7**). While the slabs produced at Naoetsu are rolled into plates mainly at the same factory, most of those produced at Nagoya are transported to Nippon Steel & Sumikin Stainless Steel's Yawata Plate Mill for rolling.

The plate mill at Naoetsu is compactly designed. It has a soaking furnace in addition to a reheating furnace, which makes it possible to re-heat rolled materials between passes. Taking advantage of this fact, the mill can produce plates of Ti-6Al-4V and hard CP titanium of JIS Class 4.

On the other hand, the Yawata Plate Mill covers a very large area (see **Fig. 8**); its quality capacity is one of the highest in the world. In addition, to secure good product flatness, a vacuum creep flattener (see **Photo 1**), capable of annealing and flattening in hot conditions, is provided exclusively for titanium plates. Its excellent flattening capacity has earned it high customer appreciation.

Copper foils for the printed circuit boards of electronic devices are manufactured through electrodeposition onto the surface of

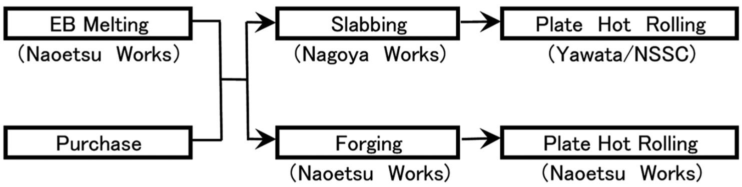

Fig. 7 Manufacturing processes of plate products

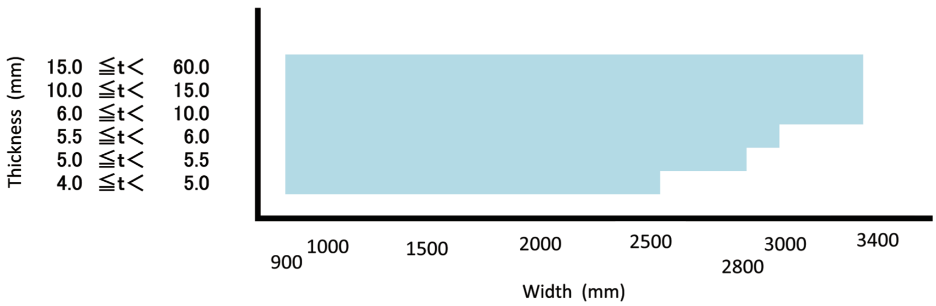

Fig. 8 Available size of plate (JIS Class 2 CP titanium)

Photo 1 Vacuum creep flattener (VCF)

drums made of titanium plates. In this process, a copper sulfate solution is electrolyzed using a titanium drum as the anode. Metallic copper is deposited on the surface of the anode drum as a foil, which is then continuously peeled off and wound into coils. Nippon Steel & Sumitomo Metal's titanium plates for this application are highly valued in the market. In this process, the drum surface is required to be metallographically homogeneous. To meet requirements, the manufacturing processes from ingot making to slab making and then to plate rolling are so designed as to obtain a highly homogeneous metallographic structure.

4.5 Welded tubes

Welded tubes of titanium are used in different sizes for plant piping for the chemical and other industries. Besides plant piping use, thin-wall welded tubes, roughly 25 mm in outer diameter, are used in great quantities for heat exchangers for condensers and the like used in power plants. Since heat exchangers are used also in seawater environments, the titanium's excellent corrosion resistance fully serves its purpose for this application. Nippon Steel & Sumitomo Metal operates tube forming lines for thin-wall welded tubes at Hikari, and manufactures tubes (12.7 to 38.1 mm in outer diameter) for the heat exchangers of condensers used in nuclear power plants and other high-end applications.

Low cost is required also for high-quality tubes for nuclear power plants, and higher productivity through higher forming-welding speed has therefore been pursued. Because of the low Young's modulus, titanium demonstrates large springback during tube forming, so high circumferential tension is applied to the tube wall when solidification of the weld pool at the seam is insufficient at high forming speeds; this may lead to product defects such as bead cracks. In addition, because the tubes are shipped welded, without grinding or other seam conditioning, to obtain smooth seams it is necessary to adequately control the line speed, taking into account both solidification speed and the pressure of shield argon gas blown to prevent oxidation.

Since the forming rolls of a tube forming line are shaped like a Coca-Cola bottle to wrap the tube wall from the outside, surface speed is different from the travelling speed of the tube material at different parts of the roll, and the tube surface is scratched or the rolls wear as a result of slippage, which means that the roll shape and the material must be selected carefully. Thanks to the appropriate selection and setting of various process factors, tube production at Hikari maintains a steadily high productivity of high-quality tubes; the products have been used for heat exchangers and condensers for nuclear and thermal power plants in and outside Japan. To stabilize product quality at higher levels, automatic diameter

Ingot	⇒	Forging (Osaka Steel Works)	⇒	Wire Rolling (Hikari Works)

Fig. 9 Manufacturing processes of titanium wire

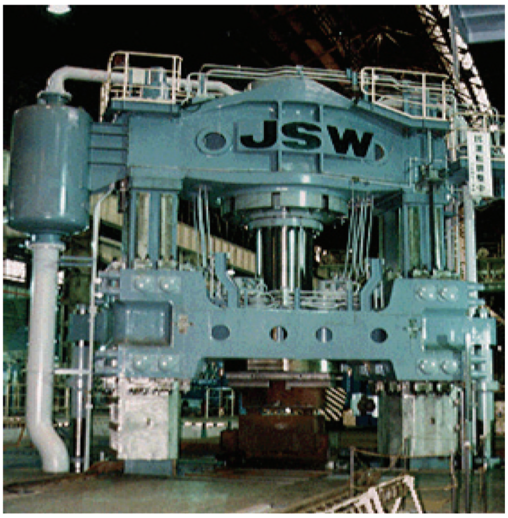

Photo 2 Forging machine in Osaka Steel Works

measurement systems have been introduced, and automatic monitoring of the butt-welding condition of the seam is being developed.

4.6 Wire rods

Before the merger, Nippon Steel had ingots forged by an outside specialist, rolled the forged ingots into billets at the section mill of Kimitsu Works, and then rolled the billets into wire rods at the Wire Rod Mill at Hikari. After the merger, it became possible to forge ingots into billets at Osaka Steel Works for wire rod rolling, as shown in **Fig. 9**; preparations are underway for transferring the billet production to Osaka. Presently, the billets produced at Kimitsu are rolled into wire rods at Hikari at the high-speed mill for steel rolling; the mill's advanced rolling technology allows production at high yields and low cost. After rolling, wire rods 6 to 15.5 mm in outer diameter undergo surface finishing processes such as special peeling (internally called "Super-Finish"), and pickling to meet different user requirements. Titanium wire rods are used mainly for eyeglasses; in addition to CP titanium, Ti-3Al-2.5V is also produced for that application. For a more fashionable appearance, Ti-15V-3Cr-3Sn-3Al, which has a higher strength and can be worked into smaller sections, has been used recently for eyeglass frames; wire rods made from this alloy are manufactured and shipped out at Hikari.

4.7 Billets and bars

The former Sumitomo Metal began its business in 1901 at Osaka Steel Works, now next door to Universal Studios Japan. The factory is now specializing mainly in wheels and wheel shafts for railway vehicles. For these products, it operates a 3,000-t forging press (see **Photo 2**), a high-speed forging machine, and a caliber rolling mill. The equipment is also used to manufacture bars and billets (up to a diameter of 350 mm) of CP titanium and titanium alloys (see **Fig. 10**). The factory also produces titanium alloy billets for aircraft applications, and has obtained accreditation from aircraft engine builders for premium-grade Ti-6Al-4V billets for the rotating parts of engines, the materials of which must be of very high quality. The billets are worked and formed by customers into jet engine rotor

Ingot ⇒ Forging (Osaka Steel Works) ⇒ High Speed Forging(GFM) (Osaka Steel Works) ⇒ Bar Rolling (Osaka Steel Works)

Fig. 10 Manufacturing processes of titanium billet

blades. (For more details on titanium products for aircraft applications, see a separate article in the present issue.)

In addition, the factory produces bars of Super-TIX™ 523AFM (Ti-5Al-2Fe-3Mo), Super-TIX™ 51AF (Ti-5Al-1Fe), etc. for such applications as auto-engine parts (valves, con rods, etc.) for motorcycles and automobiles, and golf club faces. (For more details on the former alloy, see another article in the present issue.)

5. Closing

After the merger in 2012, Nippon Steel & Sumitomo Metal became able to cover all production stages — from melting to product finishing — of a wide variety of titanium products, including sheets, plates, tubes, wire rods and bars. The newly organized company intends, through a synergistic combination of the advantages of the former two companies, to better serve customers as the world leader in the market of titanium products for general and aircraft applications.

The present issue contains various articles on unique alloys that the company has developed, as well as products for building use and aircraft applications. Readers are invited to delve into those articles for more details about many of the titanium products mentioned herein.

Kinichi KIMURA
Senior Manager, Head of Dept.
Titanium Technology & Quality Management Dept.
Titanium Technology Div.
Titanium & Specialty Stainless Steel Unit
2-6-1 Marunouchi, Chiyoda-ku, Tokyo 100-8071

Toshinori KATAYAMA
General Manager, Head of Div.
Titanium Technology Div.
Titanium & Specialty Stainless Steel Unit