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Technical Review

Expanding the Application of Titanium by Nippon Steel Corporation

Ken TERAI* Tsutomu TAKECHI

Abstract

This article introduces the approaches employed by Nippon Steel Corporation for developing and expanding the titanium applications and market. Nippon Steel has succeeded in adding superior characteristic features to titanium such as formability, designability, heat resistance, and so on, for developing titanium markets. Moreover, the company is also innovating various usage techniques of titanium products like bonding method and forming techniques, or measuring characteristic data for customers. These activities also help to expand the titanium applications and market. In this article, further trends of the applications and market of titanium are described after providing an explanation of the current titanium market.

1. Introduction

Titanium was discovered in the 1790s and is the fourth most abundant of all practical metals existing near the surface of the earth.[1] It took a long time to establish an industrial refining process for titanium. The full-scale production of this new metal was started after 1946.

The Titanium Unit of Nippon Steel Corporation is a world-class comprehensive wrought titanium manufacturer. We have developed applications for titanium and titanium alloys by utilizing their light weight, superior corrosion resistance, and high strength, have provided them with such new properties as formability, designability, and heat resistance, have developed their bonding method, forming, and other application technologies, and have maintained their property data, all from a user perspective. In this way, we have contributed to the expansion of the titanium and titanium alloy market.

In this paper, we explain the titanium and titanium alloy market situation and prospects, outline titanium application developments at Nippon Steel, and examine the future direction of titanium market developments.

2. Titanium Market Situation

Japan's wrought titanium shipments continued to increase for the fifth consecutive year since 2014, reached 18 922 tons in 2018,[2] but declined to 16 303 tons[2] in 2019, mainly due to the reductions in plant and equipment investments from the economic slowdown in China and from the restraint of thermal power plant construction against the background of environmental regulations. In 2020, the shipments fell further amid the global COVID-19 pandemic and remained at 12 544 tons.[2] The declines were especially pronounced in the aircraft and electric power fields.

The aviation sector was impacted by the sharp decrease in air passengers as countries restricted entry and locked down to counter the COVID-19 pandemic. As an index of this impact and as an index of the air travel demand, the revenue passenger kilometers (RPK) decreased by 60% in 2020 from 2019.[3] However, the aircraft demand itself has not disappeared. It is estimated that if COVID-19 countermeasures are taken in 2021, the aircraft demand will recover around 2024 to the same level as in 2019.

In the electric power field, welded titanium tubes for power plant condensers or titanium sheets (hoops) used as materials for welded titanium tubes are the main applications for titanium. Welded titanium tubes for condensers are used in thermal power generation or nuclear power generation. Welded titanium tubes for power generation in Japan, especially for nuclear power generation, have traditionally been designated as "those made in Japan" from the viewpoint of reliability. In recent years, however, such designations have been removed, and welded titanium tube manufacturers from abroad such as China and India have emerged and intensified the competition for welded titanium tube orders. In addition to this situation, lockdowns were implemented around the world for protection against COVID-19. The lockdowns decreased the global energy demand by about 6% in 2020 (7 times the impact of the 2008 financial

* General Manager, Head of Div., Titanium Marketing Div., Titanium Unit
2-6-1 Marunouchi, Chiyoda-ku, Tokyo 100-8071

crisis)[4] and also reduced the thermal power plant investments.[5]

The titanium demand in traditional main application areas of electrolysis and plate heat exchangers has been stymied by the stagnation of global economic activities under the impact of COVID-19.

On the supply side, the number of titanium suppliers for general industries is increasing, mainly in China, and the price competition is becoming fiercer. In this harsh environment of sluggish demand and increasing suppliers, we must push ahead with the development of titanium applications.

When we look at the future of the titanium market after the elimination of COVID-19, we must consider our response to the global decarbonization trend. In 2020, the Government of Japan set a goal of "2050 carbon neutral". The Ministry of Economy, Trade and Industry has disclosed specific directions for the goal.[6] The main points of the goal are to "promote electrification" and to "reduce carbon emissions during power generation by utilizing renewable energy sources and hydrogen, ammonia, and other hydrogen-rich chemicals in place of carbon". We must contribute to the achievement of the "2050 carbon neutral" goal by promoting the development of high value-added titanium applications related to these keywords while taking advantage of the lightweight, high specific strength, and corrosion resistance properties of titanium.

To expand the titanium market further, we will have to continuously strive to develop new demand for titanium ahead of other countries. We think it possible to further expand the titanium market by simultaneously achieving the two objectives of increasing titanium applications in Japan's leading industrial fields such as automobiles, home appliances, construction, and civil engineering and of substituting titanium for other materials through constant cost reduction efforts.

3. Titanium Application Field Development Trends

In the previous chapter, we outlined the titanium market situations and prospects and described the direction and necessity of titanium application development after the elimination of COVID-19. In this chapter, we explain our initiatives to develop titanium applications in the respective titanium application areas.

Figure 1 shows the classification of titanium application areas by stage. The left side shows the "existing sectors" where titanium has established its place by making use of its properties. The right side shows the "innovative sectors" where the development of titanium applications will be promoted in the future. The central part shows the areas where titanium applications have already been established and the areas where the development of new titanium applications is expected.

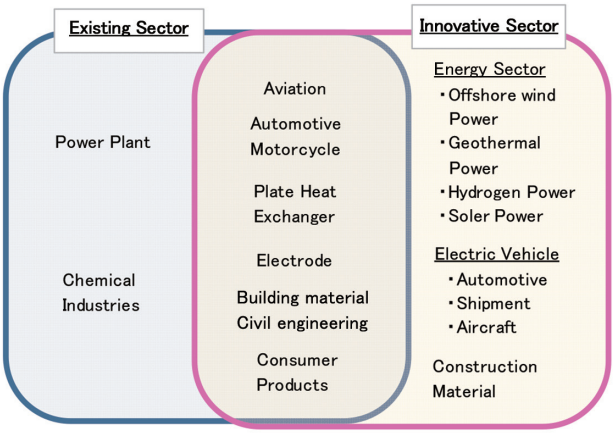

Fig. 1 Titanium products exploitation map by stage

3.1 Existing sectors

First, the "existing sectors" are described. Welded titanium tubes are used as heat transfer tubes for condensers in thermal power plants fueled by such fossil fuels as coal or oil and in nuclear power plants. This is because welded titanium tubes are valued for their maintainability and equipment stability, such as excellent seawater corrosion resistance and better erosion resistance than that of nickel-copper alloy tubes. Although this application of welded titanium tubes has been established, the specifications required of them are almost fixed and we are faced with the severe price competition with foreign welded titanium tube manufacturers such as China and India. The decarbonization trend has restricted the construction of new coal-fired power plants in developed countries.[4] Nuclear power generation is a realistic path to decarbonization, but the construction of nuclear power plants around the world is currently being promoted mainly by China and Russia.[5, 7] There is little room for Japanese manufacturers to enter.

In the chemical sector, welded titanium pipes and titanium plates are mainly used for plant equipment by taking advantage of the corrosion resistance of titanium. For example, titanium is used in the reactors of plants producing purified terephthalic acid (PTA), a raw material for PET bottles and polyethylene fibers for clothing, and in the pipes of oil refineries. China manufactures more than 40% of the PTA produced in the world. China is expected to enter a PTA plant adjustment phase because the PTA supply capacity will far exceed the PTA demand due to new PTA plant construction in 2021.[5, 8]

3.2 Central areas between "existing sectors" and "innovative sectors"

Next, the central areas with the characteristics of both "existing sectors" and "innovative sectors" are described.

3.2.1 Aircraft sector

First, we describe the aircraft sector. Aircraft are one of the major sectors where titanium has been increasingly applied. Titanium is light weight, has high specific strength and corrosion resistance, does not become brittle at low temperatures, has low thermal expansion, and can be welded/glued to carbon fiber reinforced plastics (CFRP). These properties have increased the use ratio of titanium in the latest aircraft of Airbus and Boeing. Nippon Steel has been supplying Airbus with commercially pure titanium sheets for many years. In the aviation sector, materials originally developed by manufacturers are not adopted immediately due to the importance of safety. Such materials are adopted after they have been produced, standardized, and certified. Major changes do not occur immediately. Given the decarbonization trend also in the aircraft sector, however, bio-jet fuels, electric aircraft, and hydrogen-powered aircraft are under development.[9, 10] Of course, airframe weight reduction is also required. This makes it necessary to supply lightweight and high-strength materials. Based on many years of experience in manufacturing and delivering commercially pure titanium, Nippon Steel will proceed with preparations to supply stronger titanium.

3.2.2 Automotive sector

The automobile sector is described next. The application of titanium in this sector is currently progressing mainly for motorcycles. Titanium is mostly used in the connecting rods and valves whose weight must be reduced to improve engine response and in the mufflers (**Photo 1**) that contribute to weight reduction and designability. Nippon Steel has developed the Super-TIX™ 51AF with excellent

Photo 1 Titanium muffler provided by AKRAPOVIC
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Photo 2 Titanium fuel tank for HONDA CRF450R

high temperature strength and good machinability and the Super-TIX™ 523AFM with high temperature strength and fatigue strength higher than those of general-purpose 6Al-4V alloys for connecting rods and valves. Also, we have developed the Super-TIX™ 10Cu with formability similar to that of commercially pure titanium and it is expected to be used at high temperatures of 700°C or above, the Super-TIX™ 10CUNB with improved high-temperature oxidation resistance, and the Super-TIX™ 10CSSN with improved high-temperature strength for mufflers. The Super-TIX™ 10CU series is used in not only two-wheel, but also four-wheel applications. In addition, Nippon Steel has developed the world's first titanium fuel tank (**Photo 2**) for mass-produced motorcycles. The titanium fuel tanks have been installed in mass-produced Honda motorcycles (like the CRF450R) since 2017. In 2018, Nippon Steel and Honda R&D Co., Ltd. jointly received the 34th Sokeizai Industry Technology Award (Sokeizai Center Chairman's Award) for the development of fuel tank titanium and the titanium fuel tank forming technology.

The decarbonization trend in the automobile sector prompts further improvement in fuel efficiency and is expected to accelerate electrification (HV, PHV, EV, and FC) and electric assist (MHV). Based on the technologies and products we have developed for internal combustion engines, we will contribute to the technology development for the decarbonization trend in the automobile sector by utilizing the properties of titanium such as light weight and high strength.

3.2.3 Plate heat exchanger (PHE) sector

Heat exchangers are a major titanium application area where the excellent seawater corrosion resistance of titanium is put to good use. Titanium sheets are used most in plate heat exchangers (PHE). In the PHE, heat is exchanged between a high-temperature medium and cooling seawater flowing on the front and back of each plate, respectively. Titanium sheets are press-formed into unique corrugated patterns to suit specific media. The corrugated patterns are so complicated that the titanium sheets used for the PHE must have high formability. Nippon Steel manufactures PHE titanium sheets with optimum press formability for users by selecting optimum materials and precisely controlling the microstructure and surface quality in the manufacturing process. In addition, PHEs have tended to decrease in thickness and increase in size (width) for higher performance. Nippon Steel can produce titanium sheets from 0.3 mm in thickness and to over 1 500 mm in width, depending on the thickness. We stably supply our titanium sheets to our users, thereby contributing to the increasing size and functionality of their PHEs.

PHEs made of titanium sheets have been widely used mainly in marine and shipping applications thanks to their corrosion resistance. The PHEs are expected to play an active role as heat management equipment also in the decarbonization trend. For example, the cascade exhaust gas cooling system developed by Alfa Laval AB in 2020 reduces methane from the exhaust gas of ships by 50%, improves the fuel economy, and reduces the CO_2 emissions. The system uses a seawater-cooled PHE. In renewable energy geothermal power generation, a binary power generation system exchanges heat between hot water and a power generation medium (like ammonia) to generate power. Corrosion resistant titanium is used depending on the hot spring water quality. Nippon Steel will continue to contribute to the development of decarbonization technologies by PHE manufacturers through the supply of PHE titanium sheets with excellent formability.

3.2.4 Electrolysis sector

Caustic soda (NaOH) plants are the most typical examples of titanium application in the electrolysis sector. Caustic soda is produced together with chlorine and hydrogen by the electrolysis of brine. The ion exchange membrane process is a principal caustic soda production process. Japanese manufacturers account for more than 50% of caustic soda production in the world.[5] Titanium is mainly used in the anodes that contain brine and nickel is mainly used in the cathodes that produce caustic soda. Ion exchange membrane supports are exposed to a high-temperature and high-concentration chloride ion environment. They are coated or made of corrosion-resistant titanium alloy to protect against crevice corrosion.

General corrosion-resistant titanium alloys contain 0.12 to 0.25% of the precious metal palladium and are standardized in JIS and ASTM guidelines. Given the high palladium cost, Nippon Steel offers two cost saving and corrosion resistant titanium alloys for use in caustic soda electrodes: SMIACE™ (Ti-0.06%Pd-0.5%Co: JIS Classes 17–20/ASTM Gr16,17,30,31) and TICOREX™ (Ti-0.05%Ru-0.5%Ni: JIS Classes 21–23/ASTM Gr13–15). Each has the precious metal content reduced to a third of that of general corrosion-resistant alloys and achieves almost the same crevice corrosion resistant performance. For details on these corrosion-resistant titanium alloys, see the article "Development of High Corrosion-Resistant Titanium Material with Reduced PGM Content" in this special issue.

One possible response to the decarbonization trend in the electrolysis field is the development of titanium applications in hydrogen production plants. Currently, the alkaline water electrolysis process (for producing hydrogen by electrolysis with nickel electrodes used in a KOH solution) is being increased in size. Another process that uses titanium electrodes is under development. Depending on future development results, demand may appear for cost-saving and corrosion-resistant titanium alloys in this area.

3.2.5 Building material and civil engineering sectors

For titanium applications in the building material sector, Nippon

Steel has developed titanium materials that do not discolor over many years. We have also developed titanium application technologies required to use titanium materials as building materials (design materials) and have created new titanium designs and titanium building products in collaboration with construction and decoration partners. Our titanium materials have been used in the construction of more than 600 buildings from traditional to public buildings.

Titanium building materials can develop various interference colors by adjusting the thickness of the anodized oxide film and can produce mattes with suppressed metallic luster by blasting. Various colors and textures can be expressed without using paints. A recent application example is the roofing material of the Hirosaki Museum of Contemporary Art (**Photo 3**) that opened in July 2020. The Yoshinocho brick warehouse built in the Meiji and Taisho eras and designated as a modern industrial heritage site was renovated into this first public museum in Hirosaki City as a new base for creating art and culture. The site was also that of Japan's first cider plant that began production in the war era. The renovation required lighter roofing materials to avoid weight increase due to seismic reinforcement. Also in view of snow corrosion protection, long-term building durability, and bright cider gold designability with interference colors characteristic of titanium, Nippon Steel's titanium building materials were adopted. The architectural design was performed by the Atelier Tsuyoshi Tane Architects located in Paris, France and represented by Tsuyoshi Tane who worked on the Estonian National Museum. The renovation was conducted under the architectural concept of continuing memory.

Since 2017, Nippon Steel has used the brand "Designing Titanium TranTixxii™" to refer to the titanium building materials and other titanium products that provide elegance and the titanium materials that are developed to provide such elegance. The keyword "material transcending ages" of TranTixxii™ matches the architectural concept of continuing memory of the Hirosaki Museum of Contemporary Art.

The TranTixxii™ titanium building materials were also adopted in the Katase-Enoshima station building (**Photo 4**) of Odakyu Electric Railway Co., Ltd. This building features a design imitating the Dragon Palace "Ryugu-jo" that appears in a Japanese fairy tale. The patina color often used in Japan's traditional architecture is reproduced by coloring and blasting. The ridges of the roofs are adorned with tiles of titanium sheets with the Ion Plating Gold color, Nippon Steel's patented technology. The modern Dragon Palace was completed in August 2020 through the fusion of traditional architectural technologies and the latest material technologies.

Titanium has excellent corrosion resistance, requires little maintenance after construction, and offers a low life cycle cost (LCC). It is also light weight and helps to significantly reduce the weight of roofs. For example, when titanium roof tiles were used in place of traditional fired-clay roof tiles on the roof of the main hall of the Sensoji Temple in Tokyo, the roof weight was reduced to one fifth of that before the renovation. The building's earthquake resistance was also improved. Since the titanium roof tiles are fixed to the roof, none of them fell from the roof in the 2011 Great East Japan Earthquake. In this way, titanium greatly contributes to safety and security. Titanium is a relatively new building material. Using titanium, we will contribute to the future development of society and the protection and preservation of important buildings by strengthening our efforts to protect and preserve the world's cultural and natural heritage as targeted in "Goal 11: Sustainable cities and communities" in the Sustainable Development Goals (SDGs) adopted by the United Nations.

Photo 3 Exterior of Hirosaki Museum of Contemporary Art

Photo 4 Exterior of Katase-Enoshima station, Odakyu Electric Railway Co., Ltd.

In the civil engineering sector, in collaboration with its group company Nippon Steel Anti-Corrosion Co., Ltd., Nippon Steel has been developing corrosion resistant members for steel structures by making use of the excellent corrosion resistance of titanium. The titanium sheathing and petrolatum coating method (TP method) is a method employed to ensure the corrosion protection of offshore steel structures like steel pipe piles of piers. Compared to the fiber-reinforced plastic (FRP) sheathing method, the TP method is mostly free from deterioration over time and from damage by driftage. The titanium sheathing is also recyclable. The TP method has been exposure tested for more than 35 years at the surf zone observation pier of the Hasaki Oceanographical Research Center in Kamisu City, Ibaraki Prefecture, and is expected to last for 50 years. As of September 2020, the TP method had been employed in as many as 293 projects.

The titanium foil corrosion protection method uses 0.1 mm thickness commercially pure titanium foils laminated with an adhesive and painting. The results of 23-year exposure tests on the Okinawa Expressway suggest that the method is expected to last 60 years to save maintenance and life cycle costs. In 2019 at the Tanegashima Space Center of the Japan Aerospace Exploration Agency (JAXA), a national research and development agency, the titanium foil corrosion protection method was applied to door guide rails at 80 m above ground in a large rocket assembly building for assembling, maintaining, and inspecting rockets from their factory. Titanium foil sheets are also used together with carbon fiber braces in a seismic retrofitting method that does not damage existing buildings. In 2020, the method was applied to the seismic retrofitting of the West Cocoon Warehouse at the Tomioka Silk Mill, a national treasure as well as a world heritage site. For details, refer to the article "Historical Architecture Improved by Titanium" in this special issue.

3.2.6 Consumer product sector

Titanium is not only light weight and corrosion resistant, but also causes almost no metal allergies. Also thanks to its unique texture and strength and its designability represented by TranTixxii™, titanium is used in various consumer fields. In March 2020, the TranTixxii™ titanium was adopted for the first time in the body exterior of the mirrorless digital camera "FUJIFILM X-Pro3" shown in **Photo 5** and released by FUJIFILM Corporation. The titanium alloy Super-TIX™ 20AFG, a new TranTixxii™ version, is adopted in the bezel and band of the new G-SHOCK model GMW-B5000TR-9 shown in **Photo 6** and released by Casio Computer Co., Ltd. in April 2021. We realized this application by skillfully combining optimal chemical composition and precise microstructural control in microns to satisfy all of the mirror finish, formability, and radio wave reception requirements.

At present, golf and other outdoor sports are attracting attention amid the COVID-19 pandemic. In golf, it is still fresh in the memory that Hideki Matsuyama, the first Japanese golfer in the history of the tournament, won the 2021 Masters. Our titanium alloy Super-TIX™ 51AF with light weight, high strength, and high Young's modulus is adopted in the face of the Sumitomo Rubber Industries SRIXON ZX5 golf driver (**Photo 7**) used by the same player. Titanium camping equipment has also attracted attention. New titanium products such as reusable bottles have been developed from an environmental perspective. Snow Peak Co., Ltd. marketed titanium water bottles (**Photo 8**) in April 2021. These bottles are made of Nippon Steel's commercially pure titanium sheets. As the reusable bottles contribute to the reduction of plastic waste and CO_2 emissions, they are expected to increase in usage amid the SDGs trend. Nippon Steel will contribute to society by providing titanium for use in areas close to our daily lives.

3.3 Innovative sector

Lastly, the innovative sector is described. This area is the technological field that contributes to social transformation. The principal area is those technologies oriented to the realization of carbon neutrality, and the keyword here is electrification.[6)]

The power generation areas cover technologies for utilizing renewable energy such as offshore wind, solar, and geothermal energy and for generating power from hydrogen and other carbon-free resources. Titanium's lightweight and corrosion-resistant properties are expected to play an active role in offshore wind power, house rooftop solar power, and hot spring and geothermal power generation facilities. At present, electrification is proceeding in transportation equipment that mainly uses fossil fuels. In the shipping sector, large battery-powered electric container ships were planned in Norway in the first half of the 2020s. Since September 2020 in Japan, the research and demonstration of a hydrogen fuel cell system for ships have been conducted jointly by Toshiba Energy Systems & Solutions Corporation, Kawasaki Heavy Industries, Ltd., Nippon Yusen Kabushiki Kaisha, and others.[11)] In the aircraft sector, electric aircraft has been developed by Airbus, Boeing, and JAXA, among others.[9)] Power for electrification is obtained from motors. The motors must be increased in output and decreased in weight. Titanium is expected to be applied in motors by taking advantage of its high strength and light weight. The application of high-strength and lightweight titanium will further improve the transportation efficiency of transport equipment.

The development of titanium structural members is required to build a safe and secure society in earthquake-prone Japan. The lightweight and high-strength properties of titanium are expected to reduce the weight and improve the safety of high-rise buildings and bridges. In this sector, we will also have to develop the necessary technologies and related laws and regulations.

Photo 5 FUJIFILM X-Pro3
Titanium body applied digital camera, Provided by FUJIFILM Corporation

Photo 7 SRIXON ZX5
Titanium face driver, Provided by Sumitomo Rubber Industries, Ltd.

Photo 6 G-SHOCK GMW-B5000TR-9
Titanium bezel and band applied watch, Provided by CASIO Computer Co., Ltd.

Photo 8 Exterior of titanium water bottle, Provided by Snow Peak Inc.

4. Conclusions

We have outlined the development of titanium applications by Nippon Steel. As one of the world's leading titanium manufacturers, Nippon Steel has endeavored to expand titanium application areas while responding to the needs of society and customers. Titanium is a very young metal and has been industrially used only for about 70 years. We believe that we can further develop titanium applications by improving manufacturing technologies and developing new functions to meet new applications. We will continue to develop titanium applications and technologies so that titanium can be deemed a more familiar and common metal.

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Ken TERAI
General Manager, Head of Div.
Titanium Marketing Div.
Titanium Unit
2-6-1 Marunouchi, Chiyoda-ku, Tokyo 100-8071

Tsutomu TAKECHI
General Manager, Head of Dept.
Titanium Technical Service & Solution Dept.
Titanium Technology Div.
Titanium Unit