Technical Report

Manufacturing Technology of Titanium Products for the Aerospace Industry

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Abstract

Various metal materials are used in aircraft application, but lately models using Carbon Fiber Reinforced Plastic Composite (CFRP) as the body material are becoming mainstream, and the switch from aluminum materials to titanium materials advance in the point by the affinity of the characteristic. This article introduces the main titanium materials and the titanium material manufacturing technology used for aircraft in Nippon Steel Corporation.

1. Introduction

Due to the pandemic caused by the novel coronavirus (COVID-19) that started to spread at the end of 2019, people's movements were severely restricted both domestically and globally, and the demand for air travel dropped significantly (**Fig. 1**). As of April 2021, the situation has not been improved, and there is no knowing how soon things will get back to normal. It is predicted that the demand will return to the pre-corona level around 2024.

However, despite the contingency of the pandemic, the future growth in air passenger demand is certainly guaranteed, and the preparations for post-corona life have to be promoted. In recent years, carbon-neutral (decarbonized society) has been advocated worldwide to cope with the environmental problems, and the reduction of aircraft weight has been further promoted in order to improve fuel efficiency. Thus CFRP and titanium materials are now being widely employed. **Figure 2** shows the ratio of materials used for Boeing B787.

For the usage, more ecological manufacturing technology is required for the titanium material manufacturing technology. For example, Ti-6Al-4V alloy, which is currently used widely as a titanium alloy sheet material for aircraft, has poor cold-formability, and hot-packed sheet rolling is necessary to manufacture the sheets, resulting in poor energy efficiency. We consider that we can greatly contribute to society by developing a manufacturing process of titanium sheets in a coiled form (cold-rolled finish) having equivalent perfor-

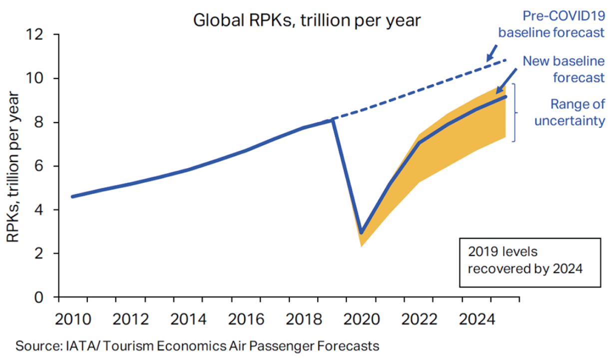

Fig. 1 Tourism economics and air passenger forecasts by IATA (International Air Transport Association)

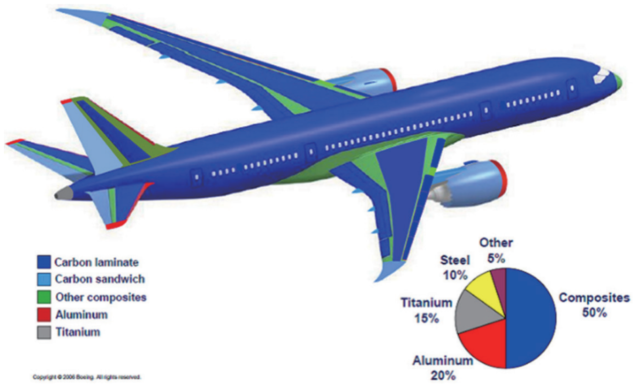

Fig. 2 Ratio of materials for B787 (using ratio of titanium and CFRP: 65%)

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mance. In addition, some aircraft parts are made by cutting out the material from a thick plate and machining it with a yield of 10% or less. Improvement in yield and the reduction of the machining man-hours of such long-length parts having an identical lengthwise sectional shape like a rail can be accomplished by employing a shaped extruded material. Such manufacturing technology is described hereunder.

2. Titanium Sheets for Aircraft

In many cases, titanium heavy plates and/or forged products are used for aircraft. However, sheets are also required. Nippon Steel Corporation manufactures commercially pure titanium and Ti-15V-3Cr-3Al-3Sn alloy titanium sheets for aircraft, which have excellent cold-formability as compared with other sheets. In addition, Nippon Steel is currently studying the application to aircraft of Nippon Steel's original alloy Super-TIX™51AF that has cold-formability and characteristics close to that of Ti-6Al-4V.

2.1 Commercially pure titanium

Commercially pure titanium is used as sheets in many aircraft because it has excellent cold-formability, and can be processed into various parts by forming at parts manufacturers. There are four grades depending on the strength level, and the materials are used according to the required strength and the forming process. The strength is determined by the amount of oxygen and/or iron contained as impurities.

Commercially pure titanium has a hexagonal close-packed crystal structure with few slip systems. Therefore, the occurrence of the twin crystal complements the limited number of slip systems.[1] Accordingly, commercially pure titanium sheets have excellent cold-formability, and are often processed exploiting this property.

It is used for non-structural members such as galleys, lavatories, ducts, cover materials, and many parts have the required corrosion resistance and formability. In addition, the application of CFRP not only to the airframe, but also to engine parts is increasing for the purpose of reducing the weight of each part. Sometimes they need to be covered for reinforcement. **Figure 3** shows an example.[2] Commercially pure titanium of Nippon Steel was applied for use as the sheath of the Structural Guide Vane (SGV, fan exit guide vane) behind the fan section of the PW1100G-JM, one of the engine types installed in the Airbus A320neo. The static vanes of the SGV are made of a composite material, and the titanium is used to protect them.

The manufacturing process of the commercially pure titanium

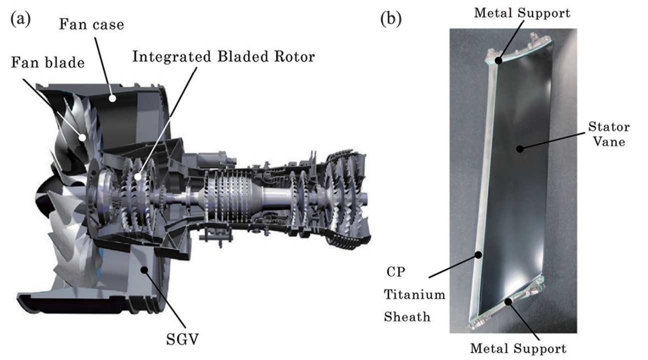

Fig. 3 Commercially pure titanium sheets application part and schematic image of PW1100G-JM[2]
(a) Cut model schematic image of PW1100G-JM and position of main parts, (b) Schematic image of SGV

sheets is almost the same for aircraft use and industrial use. However, in manufacturing, the acquisition of the Aerospace Quality Management System (JIS Q 9100) and the international special process certification system, as well as the National Aerospace and Defense Contractors Accreditation Program (Nadcap), are required, and additionally the individual accreditation and/or the quality control of customers are required as necessary.

Aerospace Material Specifications (AMS) in the U.S.A. are recognized as the material standard for aircraft. It also establishes four types of commercially pure titanium sheet. In addition, British Standards (BS) in the United Kingdom and Deutsches Institut für Normung (DIN) in Germany also establish standards for commercially pure titanium sheets for aircraft (**Table 1**). Further to these, there are also the standards of aircraft manufacturers.

In commercially pure titanium sheets, conformity with the multiples of such standards is required in many cases. This is because a variety of parts is often produced from one sheet, and the sheet standard required for the parts is different.

Furthermore, test standards depend on above standards. For example, regarding the tensile test, AMS refers to ASTM E8/E8M, BS refers to EN2002-1, and DIN refers to DIN50114 (presently superseded by ISO6892-1), and some of the aircraft manufacturers' standards require EN10002-1 (presently superseded by ISO6892-1) other than the above. It is necessary to conduct a test so that all of these standards are met.

Nippon Steel started shipping the commercially pure titanium sheets for aircraft in 1997 when Airbus was still a corporate alliance of German, French, British, and Spanish companies, and started shipping to one of them, Daimler Chrysler Aerospace AG. After that, Airbus became an integrated company in 2001, and Nippon Steel has continued to deliver up to the present day.[3]

Then later, the accreditations of Bombardier Inc. and EMBRAER, each of which is an airframe manufacturer, and of Rolls-Royce and Safran S.A, each of which is an engine manufacturer, were acquired. Although not directly accredited, the SGV using the commercially pure titanium sheets supplied to IHI Corporation has been accredited by an engine manufacturer.

Various audits are continuously conducted by these manufacturers in order to maintain accreditation.

2.2 Titanium alloy

Ti-6Al-4V is the most well-known titanium alloy and its sheets are the most widely used in aircraft. However, unlike the commercially pure titanium, they are hot-formed because of its poor cold-formability. Further, it is manufactured in Russia, the United States, etc., but not in Japan. Therefore, for aircraft use, Nippon Steel is presently working on the development of two types of alloy having excellent cold-formability as high as that of commercially pure titanium.

2.2.1 Ti-15V-3Cr-3Al-3Sn

This alloy is a β-type titanium alloy (hereinafter referred to as β alloy) developed in the United States in the 1970s.[4] Since the crys-

Table 1 Specifications of commercially pure titanium sheets for aircraft

Material	AMS	BS	DIN
Gr.1	AMS4940	BS TA1	WL3.7024
Gr.2	AMS4902	BS TA2	WL3.7034
Gr.3	AMS4900	–	–
Gr.4	AMS4901	BS TA6	WL3.7064

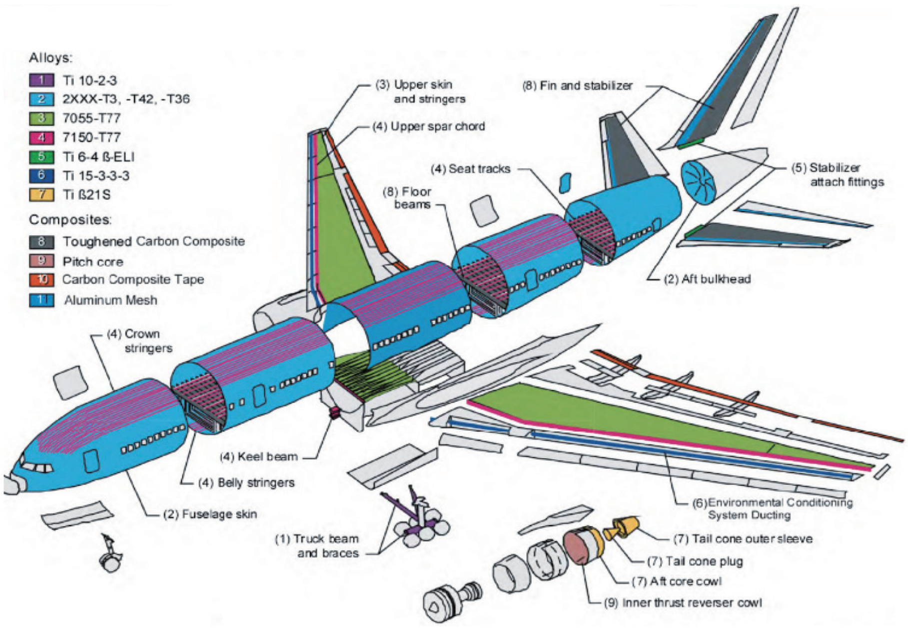

Fig. 4 Ti-15V-3Cr-3Al-3Sn sheets and other material application parts and schematic image of B777 [5)]

tal structure of β alloy is of a body-centered cubic structure like iron, it has excellent cold-formability. On the other hand, it has a feature that the strength can be increased by aging treatment. Furthermore, due to its low Young's modulus, it is also used for eyeglass frames and/or golf clubs.

For the aircraft application, it is used as aging treatment for parts requiring high strength like ducts. **Figure 4** provides an example of the application parts of Boeing B777,[5)] which shows that the material is used for the ducting of the environment conditioning system. Although commercially pure titanium or Ti-6Al-4V is used for the duct, this alloy is used when high strength and cold-forming are required.

AMS4914 is cited as the official standard, and it requires that the tensile properties after aging treatment (2 conditions) be met in addition to the chemical compositions and the mechanical properties in the annealed condition.

Nippon Steel used to manufacture this alloy for eyeglass frames and the like, and further, has established a manufacturing process that meets the standards for the supply to aircraft.

2.2.2 Super-TIX™51AF

As shown earlier, Ti-6Al-4V is most widely used as titanium alloy sheets. However, since Ti-6Al-4V is poor in cold-formability, hot-forming is applied in the forming process. Furthermore, another problem is the low sheet productivity due to the packed rolling production process.

Nippon Steel has developed a vanadium-free alloy, Super-TIX™51AF (Ti-5Al-1Fe).[6)] Currently the alloy is used for automobile engine parts and/or golf clubs and the like.

Nevertheless this alloy has strength only fractionally lower than that of Ti-6Al-4V, it has cold-formability, and production by cold rolling in a coiled form is possible (**Fig. 5**). The evaluation of the sheets proved that the product has sufficient cold-formability (**Fig. 6**). Application of the alloy to a wider range of the aircraft manufacturing field as a new alloy to replace Ti-6Al-4V is expected.

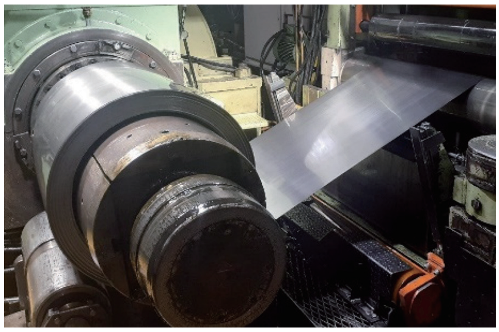

Fig. 5 Photograph of Super-TIX™51AF cold rolled sheet

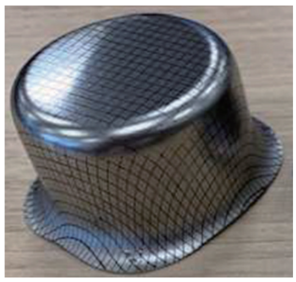

Fig. 6 Photograph of Super-TIX™51AF cold rolled sheet after cold deep drawing

3. Hot Extruded Shape for Aircraft

Hot extruded shape is manufactured by various methods such as indirect extrusion or hydrostatic extrusion. **Figure 7** shows the manufacturing process of hot extruded shape in Nippon Steel. In Nippon Steel, after heating the billet to a predetermined temperature, it is extruded to a product shaped material and pickled. After that, it is hot straightened and shipped. This section describes the details of the hot extrusion and the hot straightening.

3.1 Hot extrusion

Nippon Steel employs the Ugine-Sejournet process for hot ex-

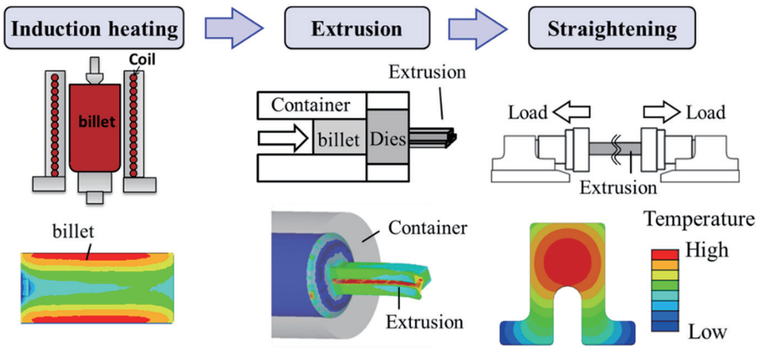

Fig. 7 Temperature distribution in each manufacturing process calculated by FEM analysis in titanium alloy billet or extrusion

trusion processing. In this process, the hot extrusion is conducted by heating a billet to a predetermined temperature to make the hot-work easier, setting the billet on the horizontal hydraulic type pushing pressing machine, and extruding the billet in a short time through a die hollowed out to the sectional shape of the product. Figure 7 shows the schematic drawing. The extrusion is delivered to the next processing stage after the pickling process. Further, as explained later, the billet heating temperature is determined by FEM analysis so that the temperature distributions from the billet heating to the extrusion become best-optimized.

The Ugine-Sejournet process[7] is a process that produces bars, tubes, and shaped bars of various metals by using glass as a lubricant. It was invented in 1942, and the first application was to carbon steel[8] followed by promotion to the nonferrous metals such as aluminum,[9] copper and copper alloys,[10] and so forth. Compared with aluminum, copper, and copper alloys, the titanium alloys have higher deformation resistance, and the heat generation during working and processing is high. Generally the billet is heated to the β single phase temperature region, and extruded. However, titanium is chemically active, and as observed to be problematic in machining, it adheres to the opponent metal on contact with it, and inflicts strong wear on the opponent metal.[11] Therefore, compared with the case of the extrusion of other metals, due to the adhesion and/or the eutectic reaction, the wear of the die and/or the pushing jig is large, so the selection of the billet heating temperature, lubricant, die shape and die material is important.

3.2 Hot straightening

Bend and/or torsion remain in the extruded shape. As compared with the steel extrusion, the extrusion of titanium alloy has high strength and low elasticity, and exhibits large spring-back at room temperature. Therefore, straightening at room temperature is difficult, and such bend and/or torsion are mainly corrected in a hot state. Nippon Steel straightens the extruded shape in a hot state by using an electric heating and stretching type straightener. As the schematic drawing shows, the shaped material is electrically heated while having both its ends clamped and held by jigs designed to fit the sectional shape of the shaped material, and hot straightened by exerting torsional and tensional deformation as it is. Thus the shaped material is straightened by holding hot for a predetermined period of time, and then cooled. The condition for straightening is stipulated in the standard designated by the end user aircraft manufacturer (e.g. AMS4935, etc.). The production condition is minutely adjusted within the allowable range to control the form and the dimension accuracy of the shaped material after straightening.

3.3 Analysis

In the manufacturing process of the titanium alloy shaped material, in the hot extrusion process, it is important to compatibly achieve the acceptable shape dimensions, microstructure and mechanical properties, and in the hot straightening process, the reduction of the residual stress to obtain excellent shape even after machining in addition to the straightness after the straightening process is important. An FEM analysis considering creep and the thermal strains were developed to determine the heating temperature, die design, and the extruding speed in the hot extrusion and to determine the heat history and the straightening force in the hot straightening. A technology that estimates the microstructure and material characteristics based on the analyzed temperature and strain history was established. Thus the production conditions for various shaped materials are determined. Figure 7 shows an example of the FEM analysis in each manufacturing process. The temperature and the strain distributions of the hot extruding and the hot straightening are grasped to stabilize the quality.

4. Summary

The use of titanium material as an airframe material for aircraft is expected to grow in future, as will its importance. Under such a situation, our role as the material manufacturer is to establish lower costs for higher quality, and an eco-friendly manufacturing process. Titanium is often considered to be an anti-ecological metal because it consumes a large amount of electricity in its manufacturing process (especially the extraction process from raw material ore). However, it is maintenance-free (high corrosion resistance), and has a long service life compared with other materials. It is an eco-friendly material in the long run. We will contribute to the solution of environmental problems as much as possible by making full use of the cold-formability and the production technologies that enhance the yield with the near-net shaped material as explained above. On the other hand, strict quality control is required for the aircraft materials from the viewpoint of ensuring safety, and Nippon Steel has a history of strictly maintaining the quality requirements of aircraft manufacturers. Hereafter, we are determined to contribute to the world by developing and expanding the manufacturing technology for more eco-friendly titanium while maintaining the quality management as well.

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