

Application and Features of Titanium for the Aerospace Industry

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Abstract

In the field of aerospace, titanium has been applied for many years. Commercially pure titanium and titanium alloy as represented by Ti-6Al-4V are mainly used for the airframe and the engine parts respectively. The demand expansion of titanium has been expected due to realize low fuel consumption of aircraft. On the other hand, various qualifications and high quality management are required in order to entry in the aerospace industry. This paper describes the application situation of present state, titanium materials for the aerospace applications and our efforts in regard to the issues for expanding the use of titanium in this field.

1. Introduction

Commercially pure titanium and titanium alloys for industrial use (hereinafter referred to as “titanium”) are widely used for aircraft as a material having light weight (density being 60% that of steel), high strength, and excellent corrosion resistance. Recently, the application ratio of CFRP (Carbon Fiber Reinforced Plastic) to airframes and engine parts has been growing to improve aircraft fuel consumption. Similarly, demand for titanium is also growing as it has excellent compatibility with CFRP with respect to corrosiveness and coefficient of thermal expansion issues. The amount of titanium used in the low fuel consumption aircraft A350XWB manufactured by Airbus S.A.S., where a large amount of CFRP is used, has grown to more than twice the amount used in conventional aircraft.¹⁾ Furthermore, at the 28th ITA (International Titanium Association) General Meeting held in October, 2012, it was reported that demand for aircraft in the future will remain stable. Indeed, an increase in titanium demand is foreseen, as shown in Figs. 1 and 2.²⁾

Nippon Steel & Sumitomo Metal Corporation acquired qualifications in 1985 from Rolls-Royce and domestic heavy industry manufacturers, and started commercial production of titanium alloys for aircraft engines. Furthermore, the company concluded a long term agreement with Airbus in 2002, and has been consistently supplying pure titanium for their airframes. Entry into the aircraft industry and expansion of applications cannot be successfully accomplished without high quality control, the acquisition of various accreditations, and precise operation control.

This report describes the current status of titanium applications in aircraft and approaches to resolve associated issues.

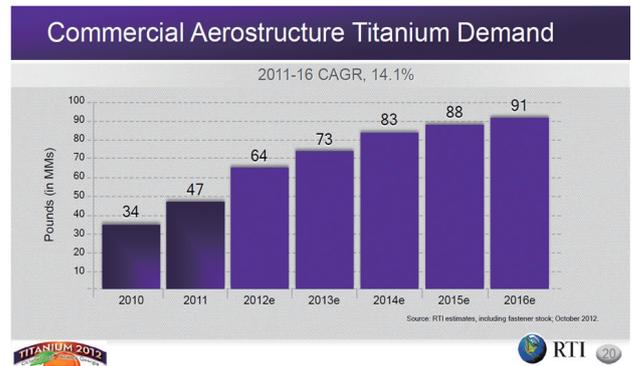


Fig. 1 Commercial aerostructure titanium demand published by RTI in 2012 ITA

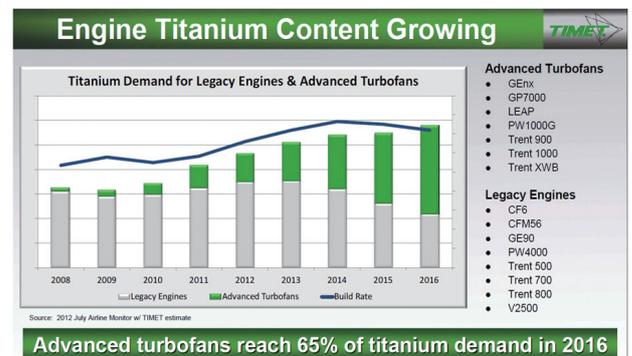


Fig. 2 Engine titanium content growing published by TIMET in 2012 ITA

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2. Current Status of Titanium Applications for Aircraft

2.1 Titanium for airframes

Starting with fabric and wooden materials, airframe materials have evolved into the current CFRP by way of aluminum alloys. Additionally, steel-based materials were used for portions where high strength was required (frames and joints), and have now been replaced by titanium alloys to save weight. Designing joints in an airframe where heterogeneous materials are used must take into consideration the prevention of potential difference corrosion (galvanic corrosion), and the elimination of strain caused by a difference in coefficients of thermal expansion. In recent years, as CFRP has come to the forefront, titanium alloys with physical characteristics similar to those of CFRP have become more commonly used.

2.2 Titanium for engines

Turbo fan engines are widely employed by commercial aircraft to improve combustion efficiency, and thereby improve fuel consumption. Fuel combustion in the rear section of the engine runs the gas turbine and fan blades in the fore section. Propulsion thrust is generated by the reaction force of the rearward flow of air taken in from the front by the blades, and the rearward discharge of combustion gases.

Turbo fan engines of this type consist of four sections. They are, in order from the front: the fan, compressor, combustion chamber, and turbine. A titanium alloy is mainly used for the fan and the compressor in the fore half section, where the temperature is relatively low (600°C or lower). For the turbine and the combustion chamber in the rear half section where temperatures are higher, a nickel-based alloy or iron-based alloy is used.

2.3 Properties required for titanium material in aircraft

Airframe maintenance costs can be effectively reduced through the use of materials excellent in fatigue strength, crack propagation resistance, fracture toughness, and corrosion resistance. Furthermore, titanium alloys are widely used due to their aforementioned compatibility with CFRP. Examples of applications of titanium alloys for airframes with respect to location and material are shown in **Table 1**. In that table, numerical figures shown in "Material" denote the general content of major elements. For example, Ti-6Al-4V represents an alloy containing aluminum (Al) of 6wt% and Vanadium (V) of 4wt%.

For aircraft engines, titanium alloys stronger than pure titanium are used for their light weight, high strength (high specific strength) and heat resistance properties. Aluminum alloys with high specific strength are rarely used in aircraft engines because their strength drops sharply at temperatures of about 200°C and above. Although the specific strength of titanium alloys deteriorates as the temperature rises, their specific strength is superior to that of Ni-based alloy in the temperature range between 500-600°C.

Since the temperature around fan blades is relatively low, Ti-6Al-4V alloy having a higher specific strength and excellent fatigue

strength is commonly used. For engines of medium and small size aircraft, forged solid fan blades are employed, while on the other hand, for large engines with larger fan blades, hollow fan blades devised for saving weight are employed. The fan disc fixes fan blades together and is considered to be the most important safety related part. For this reason, materials having a high strength and high toughness are required, and therefore, titanium alloys such as Ti-6Al-4V and Ti-17 (Ti-5Al-2Sn-2Zr-4Cr-4Mo) are used.

Temperatures in high-pressure compressors become higher than in low-pressure compressors, and a high strength material with high heat resistance is therefore required. As for compressor blades, Ti-6Al-4V alloy is used for low-pressure compressors, while Ti-8Al-1Mo-1V and Ti-6Al-2Sn-4Zr-6Mo, which have excellent strength and fatigue characteristics and toughness at high temperatures, are used for high-pressure compressors. For compressor discs, excellent low-cycle fatigue and creep characteristics are required, in addition to high strength and toughness at high temperatures; therefore, Ti-6Al-2Sn-4Zr-2Mo-0.1Si and Ti-6Al-2Sn-4Zr-6Mo titanium alloys, which offer excellent heat resistance, are used.

2.4 Examples of titanium material for aircraft

Major titanium materials used in airframes and engines are introduced hereunder.

(1) Commercially pure titanium

There are four grades of commercially pure titanium, categorized by strength, so the most appropriate material can be selected according to the required strength and workability. They are used for non-structural applications, such as water supply systems for galleys and sanitary, and for ducts and piping, many of which require corrosion resistance and good formability.

(2) Ti-6Al-4V alloy

Ti-6Al-4V alloy is designed for a good balance of characteristics, including: strength, ductility, fracture toughness, high temperature strength, creep characteristics, weldability, workability, and thermal processability (higher strength is easily obtained by heat treatment). This alloy is therefore used for many airframe and engine parts. Furthermore, there are many actual applications of this alloy in aircraft where high reliability is required, and further, the availability of abundant data promotes its application. In airframes, it is used for general structural material, bolts, seat rails and the like. In engines, due to the relatively low allowable temperature of about 300°C, the alloy is used for fan blades, fan case and the like in the intake section where temperatures are relatively low. Major relevant standards are JIS H 4600 (TAP 6400H) and ASTM G5. The yield strength of annealed material is 825 MPa or higher, tensile strength is 895 MPa or higher, and elongation is 10% or higher at room temperature.³⁾

(3) Ti-6Al-2Sn-4Zr-2Mo alloy

Ti-6Al-2Sn-4Zr-2Mo alloy is a heat resistant alloy developed in the latter half of 1960s. Its heat resistant temperature is approximately 450°C. In the latter half of the 1970s, Ti-6Al-2Sn-4Zr-2Mo-0.1Si was developed to improve oxidation resistance and creep property with the addition of Si of 0.06~0.2wt%, and the heat resistant temperature was improved to approximately 500°C. Therefore, this alloy is commonly used for compressor discs where 500°C is the upper service temperature limit. In order to obtain a good balance between fatigue property and creep property, Ti-6Al-2Sn-4Zr-2Mo-0.1Si alloy is, in many cases, processed to a Bi-Modal structure with the area ratio of equiaxed α grain being controlled to within 10-25%.⁴⁾ The major relevant standards are AMS 4919, 4975, and 4976. The yield strength of annealed material of the alloy is 860

Table 1 Examples of application of titanium alloys for airframe

Material	Example of application
Ti-6Al-4V	Cockpit window frame, Wing box, Fastener
Ti-3Al-2.5V	Hydraulic pipe
Ti-10V-2Fe-3Al	Landing gear, Track beam
Ti-6Al-2Sn-4Zr-2Mo	Exhaust, Tail cone
Ti-15V-3Cr-3Sn-3Al	Duct

MPa or higher, tensile strength is 930 MPa or higher, and elongation is 10% or higher at room temperature.³⁾ As the alloy has less β phase than Ti-6Al-4V alloy, ageing treatment is not effective. Therefore, the alloy is normally used after solution heat treatment (at a temperature at least 35°C below the β transformation temperature), followed by stabilizing annealing (for about 8 hours at 590°C).

(4) Ti-8Al-1Mo-1V alloy

Ti-8Al-1Mo-1V alloy was developed in the 1960s. Its heat resistant temperature is approximately 400°C. Since its heat resistant temperature is higher than that of Ti-6Al-4V alloy, it is used for compressor blades and the like, rather than fan blades. The major relevant standards are AMS 4915, 4916, 4972, and 4973. The yield strength of the annealed material is 930 MPa or higher, tensile strength is 1,000 MPa or higher, and elongation is 10% or higher at room temperature.³⁾ Similar to Ti-6Al-2Sn-4Zr-2Mo-0.1Si, this alloy has less β phase and is therefore used after solution heat treatment and stabilizing annealing.

(5) Ti-5Al-2Sn-2Zr-4Cr-4Mo (Ti-17) alloy

Ti-5Al-2Sn-2Zr-4Cr-4Mo alloy (occasionally referred to as “Ti-17” alloy) was developed in the USA in the 1970s as an alloy having high strength and excellent fracture toughness. Its heat resistant temperature is approximately 350°C. In commercial aircraft engines, the fan and shaft are built as one piece to reduce engine weight. The yield strength and tensile strength at room temperature are about 1,150 MPa and about 1,250 MPa respectively, higher than those of Ti-6Al-4V alloy by about 200 MPa. The alloy also exhibits excellent crack propagation characteristics, and is appropriate for damage tolerance design. The major relevant standard is AMS 4955. The yield strength of the STA (Solution Treatment and Aging) material is 1,055 - 1,193 MPa, tensile strength is 1,124 - 1,265 MPa, and elongation is 5% or higher at room temperature.³⁾

(6) Ti-6Al-2Sn-4Zr-6Mo alloy

Ti-6Al-2Sn-4Zr-6Mo is a titanium alloy developed around 1966. Its heat resistant temperature is about 450°C. This alloy has high strength and excellent creep characteristics. The major relevant stan-

dard is AMS 4981. The yield strength of the STA material is 1,105 MPa or higher, tensile strength is 1,170 MPa or higher, and elongation is 10% or higher at room temperature.³⁾

(7) Ti-15V-3Cr-3Sn-3Al alloy

Ti-15V-3Cr-3Sn-3Al alloy was developed around 1980. This solution heat-treated material has excellent cold workability and, in the form of a thin sheet, a strength higher than that of pure titanium JIS H 4600 (TP550H) can be obtained. For airframes, welded pipes and ducts made by welding thin sheets are used. The major relevant standard is AMS 4914. Yield strength of the solution heat-treated material is 690-835 MPa, tensile strength is 745-945 MPa, elongation is 12% or higher, the yield strength of STA material is 965-1,170 MPa, tensile strength is 1,000 MPa or higher, and elongation is 7% or higher.³⁾

(8) Ti-10V-2Fe-3Al alloy

Ti-10V-2Fe-3Al alloy has excellent hardenability, high strength, and high fatigue strength. It is mainly used for landing gear (part of the main landing gear for take-off and landing). Major relevant standards are AMS 4983, 4984, 4986, and 4987. The yield strength of the STA material is 1,105 MPa or higher, tensile strength is 1,240 MPa or higher, and elongation is 4% or higher at room temperature.³⁾

3. Examples of Application of Titanium in Aircraft

3.1 Titanium for airframes

The two biggest aircraft manufacturers in the world are the Boeing Company in the USA and Airbus S.A.S. in Europe. Although Boeing is better known in Japan, Airbus is also obtaining an increasing presence there, with delivery of its aircraft reaching 100 in March, 2013. **Figure 3** gives the names of Japanese companies that have joined the development of the A380 (full double-deck type with a seating capacity of 525 in a standard cabin configuration), the biggest aircraft manufactured by Airbus. Twenty-one Japanese companies including Nippon Steel & Sumitomo Metal are listed. This demonstrates a strong bond between Airbus and the Japanese aero-

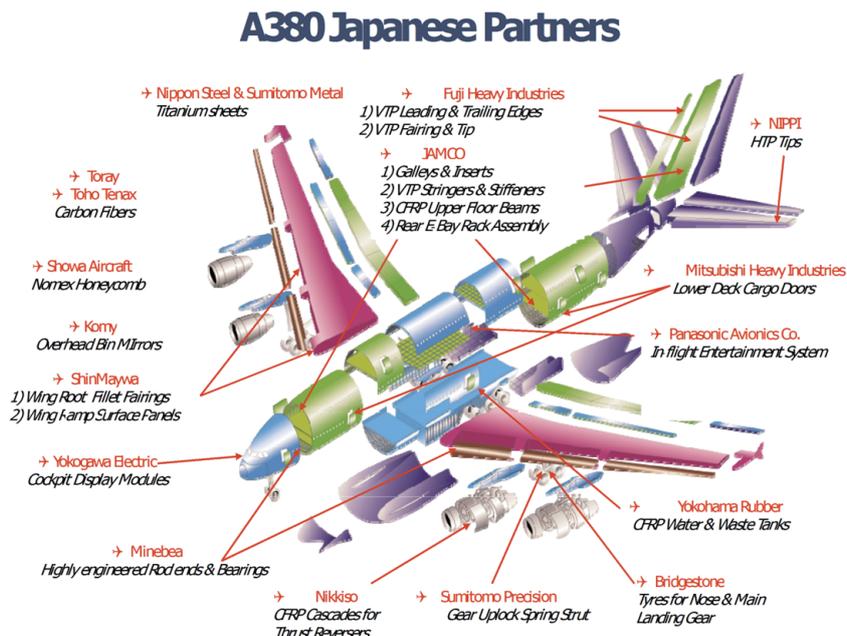


Fig. 3 Japanese suppliers for A380 ((C)AIRBUS)

Table 2 Purpose of titanium application on aerospace

① Weight saving
② Heat resistance
③ Resistance to embrittlement at low temperature
④ High corrosion resistance
⑤ Low-thermal expansion

space industry. Affiliation between Nippon Steel & Sumitomo Metal and Airbus dates back to 1997, when Airbus was merely a consortium of companies in Germany, France, the UK and Spain.

Nippon Steel & Sumitomo Metal originally delivered pure titanium sheets to Daimler Chrysler AG in Germany and to the Aerospace Corporation. Later in 2001, Airbus became an integrated enterprise, and since 2002 Nippon Steel & Sumitomo Metal has continued to deliver pure titanium sheets. Pure titanium sheets delivered to Airbus are produced based on standards specified by the company, and stable quality and delivery control are crucial. In order to achieve this, acquisition of the Aerospace Quality Management System (JIS Q 9100) and the international special process accreditation program (Nadcap: National Aerospace and Defense Contractors Accreditation Program) were required. Occasionally, specific control is required by Airbus.

Titanium application purposes for aircraft are shown in **Table 2**. Outside temperatures during flight can be -60°C or lower; however, titanium is resistant to embrittlement at low temperatures. Furthermore, there is no concern about corrosion even when dew condenses after a drop in temperature. Moreover, since its low thermal expansion is close to that of CFRP, titanium proves to be a material appropriate for aircraft. Commercially pure titanium is equipped with all of the characteristics ① to ⑤ listed in Table 2, and is therefore used for various airframe parts. Examples of such applications are the nacelle at the entry of an engine, parts of the pylon for hanging engines, and hot air piping (bleed air tubes) that prevents freezing. These parts require reliable performance, irrespective of the size of the airframe and design, and Nippon Steel & Sumitomo Metal has long devoted itself to quality stabilization, and has as a result received high appreciation from customers.

3.2 Titanium for aircraft engines

Figure 4 shows examples of titanium alloy applications for the V2500 engine employed by Airbus A320. The V2500 engine is manufactured by International Aero Engines, an international joint venture that includes Japanese enterprises. Nippon Steel & Sumitomo Metal has a dependable record delivering titanium alloys to the company over more than 25 years. Materials produced are mainly bars for the forging of fan case, low-pressure compressor blades, and the like. Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo-0.1Si alloys are most commonly used, and effective production technologies of such materials have been put into practice, providing high quality in a wide range of sizes, from 30mm diameter small bars to billets exceeding 300mm. Since foreign substances can be introduced into the material during the ingot manufacturing process, which can then be the origin of the fatigue fracture during operations,⁵⁾ contamination prevention for aircraft engines is crucial.

At Nippon Steel & Sumitomo Metal, contamination prevention is achieved with thorough equipment cleaning control, for which the company has obtained high praise from customers. Furthermore, Nippon Steel & Sumitomo Metal acquired certification under the in-

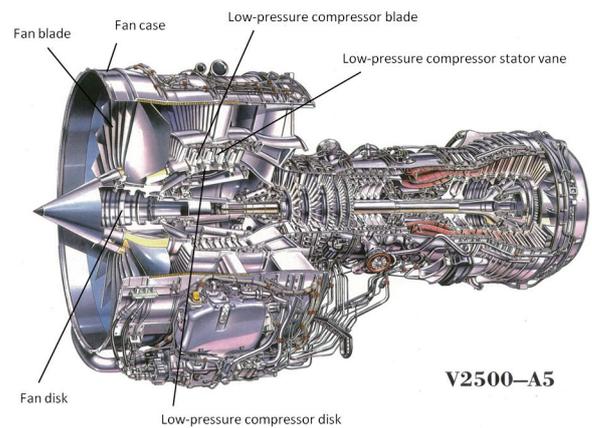


Fig. 4 Example of the application of titanium alloy for aero engine (by courtesy of Japanese Aero Engines Corporation)

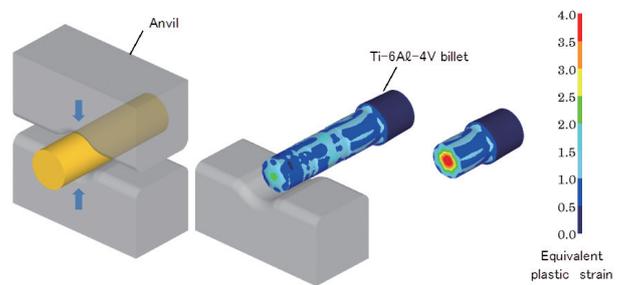


Fig. 5 Distribution of equivalent plastic strain during hot forging calculated by FEM analysis in Ti-6Al-4V billet

ternational special process accreditation program (Nadcap), as well as the qualifications of General Electric, Rolls-Royce and domestic heavy industry manufacturers in the fields of nondestructive testing, such as ultrasonic testing, and material testing (conducted by Nippon Steel & Sumikin Technology Co., Ltd.), thereby meeting their demand for high quality.

On the other hand, while ensuring quality in the titanium ingot forging process, it is also important to determine a forging schedule for the most efficient operation.⁶⁾ Finite Element Method analysis is applied as a tool for studying optimization of the forging ratio, the amount of forging reduction, the amount of feeding in forging, forging speed, and the like. Technologies for quicker and more accurate analysis have been established by applying a deformation resistance model obtained through high temperature compression testing of materials actually applied to titanium forgings. **Figure 5** shows an example of forging analysis. Quality stabilization and cost reduction can be promoted by selecting the forging schedule that produces optimum surface strain and center strain.

4. Expansion of Titanium Applications for Aircraft

Generally, although improvement in competitiveness with respect to cost, time span (from receipt of order to delivery), and quality is important, especially in the case of expansion of application to aircraft, the acquisition of various accreditations and the maintenance and improvement of quality become necessary. The approach to acquiring various accreditations, and maintenance and improvement of quality through quality monitoring control, are described below.

4.1 Acquisition and maintenance of accreditation

Titanium materials for aircraft require consistently stable quality and delivery performance, as well as certifications from the Aerospace Quality Management System (JIS Q 9100) and the international special process accreditation program (Nadcap).

The Aerospace Quality Management System (JIS Q 9100) is a standard equivalent to the international quality management system for the aerospace industry (IAQG 9100 Standard). It was developed by the IAQG (International Aerospace Quality Group), which was established in 1998 by world major aerospace enterprises aiming to improve quality and cost. The system is standardized as AS 9100 in the USA and as EN 9100 in Europe. Since JIS Q 9100 is recognized as compatible with those standards, once a Japanese enterprise acquires JIS Q 9100 certification it is registered on the IAQG-OASIS database (Online Aerospace Supplier Information System), and accepted by American and European customers as a certified enterprise.⁷⁾

JIS Q 9100's development has been based on the current prevailing quality management system (JIS Q 9001), and embodies additional requirements specific to the aerospace industry, such as Measurement and improvement of product quality and on-time delivery performance, and Requirement of consideration of First Article Inspection (FAI) as a means of verifying production processes. Since it is a standard for quality management systems, any company intending to enter the aerospace industry must first acquire certification indicating it meets the standard. After certification acquisition, audits are conducted once every year and renewal audits are carried out once every three years.

On the other hand, the international special process accreditation program (Nadcap) is an accreditation system operated by the Performance Review Institute (PRI), an American NPO. World prime contractors for airframes, engines and onboard equipment for such enterprises as Airbus, Boeing, Rolls-Royce and GE participate in the PRI system. As opposed to the IAQG 9100 standardized system for global application, where a public third party acts as the accreditation organization, prime contractors in the aerospace industry participated in the formation of an accreditation organization (the PRI), and various requirements for prime contractors are being harmonized effectively within the organization. Consequently, Nadcap has become an industry-managed system aiming to reduce redundant audits that prime contractors were conducting individually. It also focuses on reducing the number of similar audits conducted by prime contractors for suppliers who supply products of an identical standard to multiple prime contractors.

Currently, PRI is active in the USA, Europe, Japan and China, among other countries. Although application for Nadcap accreditation is to be made online to PRI headquarters in the USA, auditors are also regionally assigned and dispatched from countries other than the USA. Auditors are all experts, highly knowledgeable in the field of auditing relevant issues. Auditing at a very high level is conducted irrespective of the nationalities of the auditors.⁸⁾ There are a number of hurdles standing in the way of Nadcap certification. Firstly, all forms to be submitted and relevant in-company operating procedures and manuals must be prepared in English. Often this requires a great amount of translation into English, especially at the first stage.

Furthermore, auditing normally takes several days, because auditors personally conduct on-the-site inspections at multiple operations, and, because auditing is carried out in English, preparatory work is also required. Also, since any issues that are identified have

to be answered to other auditors stationed in the USA, the background of these issues also has to be explained. Accordingly, the content to be described in papers becomes important, and answers in correct English are prioritized. In this way, Nippon Steel & Sumitomo Metal has acquired Nadcap-HT (Heat treatment) certification at its Naoetsu Works and at a facility in Hikari Works operated by Nippon Steel & Sumikin Stainless Steel Corporation, as well as Nadcap certifications for NDT (nondestructive testing) at Osaka Steel Works, and for material testing at Nippon Steel & Sumikin Technology.

4.2 Quality monitoring control

In the Aerospace Quality Management System (JIS Q 9100), "measuring, analyzing and improving" are specified. In order to verify quality management system adaptability to product requirements, it is specified that "determination of applicable methods, including statistical methods, and the extent of their applications must be stated." In applications for aircraft, effective application of these requirements needs to be addressed. At Nippon Steel & Sumitomo Metal, key characteristics⁹⁾ were selected, and process capability is being measured. Key characteristics, chemical compositions, mechanical properties and other key control items in the respective production stages were selected where quality is monitored through statistical control on a daily basis. As for trend control, quality transition is watched in addition to process capability monitoring, and preventive improvement steps are developed.

At Nippon Steel & Sumitomo Metal, as a part of quality monitoring control, statistical control is being proactively employed. Furthermore, the company has recently established its own quality monitoring system. Material testing data, forging data and actual production data for material yield, etc. are compiled in a database. The system is designed to provide quality trends in a visualized form, and to enable easy study of interrelations among such characters. The system is being utilized for quality improvement and cost reduction. A forging logging system capable of acquiring forging data in real time was also introduced, and the system is being used for feed-back and operator training.

5. Conclusion

Demand for titanium for airframes and engines is increasing, accompanied by improvements in aircraft fuel consumption. Various titanium materials are used for aircraft, each material selected according to use. Commercially pure titanium is used for airframes where formability is considered important; for engines where heat resistance and strength are considered important, titanium alloys are used.

Nippon Steel & Sumitomo Metal has acquired qualifications from Airbus in France, Rolls-Royce in the UK, and domestic heavy industry manufacturers, and has continued to produce titanium for airframes and engines over many years. When the company acquired certifications for the Aerospace Quality Management System (JIS Q 9100) and international special process accreditation program (Nadcap), the company made various quality improvements and has obtained the praise of customers.

In the future, in order to further expand the application of titanium to aircraft, Nippon Steel & Sumitomo Metal is determined to acquire further accreditations covering a wider range of processes, and to enhance its level of quality control.

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