Chapter 2

Introduction to Selection of Titanium Alloys

General Background

TITANIUM is a low-density element (approximately 60% of the density of steel and superalloys) that can be strengthened greatly by alloying and deformation processing. (Characteristic properties of elemental titanium are given in Table 2.1.) Titanium is nonmagnetic and has good heat-transfer properties. Its coefficient of thermal expansion is somewhat lower than that of steel and less than half that of aluminum. Titanium and its alloys have melting points higher than those of steels, but maximum useful temperatures for structural applications generally range from as low as 427 °C (800 °F) to the region of approximately 538 °C to 595 °C (1000 °F to 1100 °F), dependent on composition. Titanium aluminide alloys show promise for applications at temperatures up to 760 °C (1400 °F).

Titanium and titanium alloys are produced in a wide variety of product forms, with some examples shown in Fig. 2.1. Titanium can be wrought, cast, or made by P/M techniques. It may be joined by means of fusion welding, brazing, adhesives, diffusion bonding, or fasteners. Titanium and its alloys are formable and readily machinable, assuming reasonable care is taken.

Some specific examples of product forms are:

Mill products

- Ingot
- Billet
- Bar
- Sheet
- Strip
- Tube
- Plate

Nonmill products

- Sponge
- Powder

Customized product forms

- Forgings
- P/M items
- Castings

Table 2.1 Physical and mechanical properties of elemental titanium

Property	Description or value
Atomic number	22
Atomic weight	47.90
Atomic volume	10.6 *W*/*D*
Covalent radius	1.32 Å
Ionization potential	6.8282 V
Thermal neutron absorption cross section	5.6 barns/atom
Crystal structure	
Alpha (≤882.5 °C, or 1620 °F)	Close-packed hexagonal
Beta (≥882.5 °C, or 1620 °F)	Body-centered cubic
Color	Dark gray
Density	4.51 g/cm^3 (0.163 lb/in.^{3})
Melting point	1668 ± 10 °C (3035 °F)
Solidus/liquidus	1725 °C (3135 °F)
Boiling point	3260 °C (5900 °F)
Specific heat (at 25 °C)	0.5223 kJ/kg · K
Thermal conductivity	11.4 W/m · K
Heat of fusion	440 kJ/kg (estimated)
Heat of vaporization	9.83 MJ/kg
Specific gravity	4.5
Hardness	70 to 74 HRB
Tensile strength	240 MPa (35 ksi) min
Young's modulus	120 GPa (17×10^6 psi)
Poisson's ratio	0.361
Coefficient of friction	
At 40 m/min (125 ft/min)	0.8
At 300 m/min (1000 ft/min)	0.68
Coefficient of linear thermal expansion	8.41 μm/m · K
Electrical conductivity	3% IACS (where copper = 100% IACS)
Electrical resistivity (at 20 °C)	420 nΩ · m
Electronegativity	1.5 Pauling's
Temperature coefficient of electrical resistance	0.0026/°C
Magnetic susceptibility (volume, at room temperature)	180 (±1.7) × 10^{-6} mks

One of many different types of investment cast titanium parts now produced is shown in Fig. 2.2. Figure 2.3 shows a large forged titanium part. This part weighs approximately 1400 kg (3000 lb).

Titanium has the ability to passivate and thereby exhibit a high degree of immunity against attack by most mineral acids and chlorides. Pure titanium is nontoxic; commercially pure titanium and some titanium alloys generally are biologically compatible with human tissues and bones.

The excellent corrosion resistance and biocompatibility coupled with good strengths make titanium and its alloys useful in chemical and petrochemical applications, marine environments, and biomaterials applications. The combination of high strength, stiffness, good toughness, low density, and good corrosion resistance provided by various titanium alloys at very low to elevated temperatures allows weight savings in aerospace structures and other high-performance applications.

Selection of Titanium Alloys for Service

Primary Aspects. Titanium and its alloys are used primarily in two areas of application where the unique characteristics of these metals

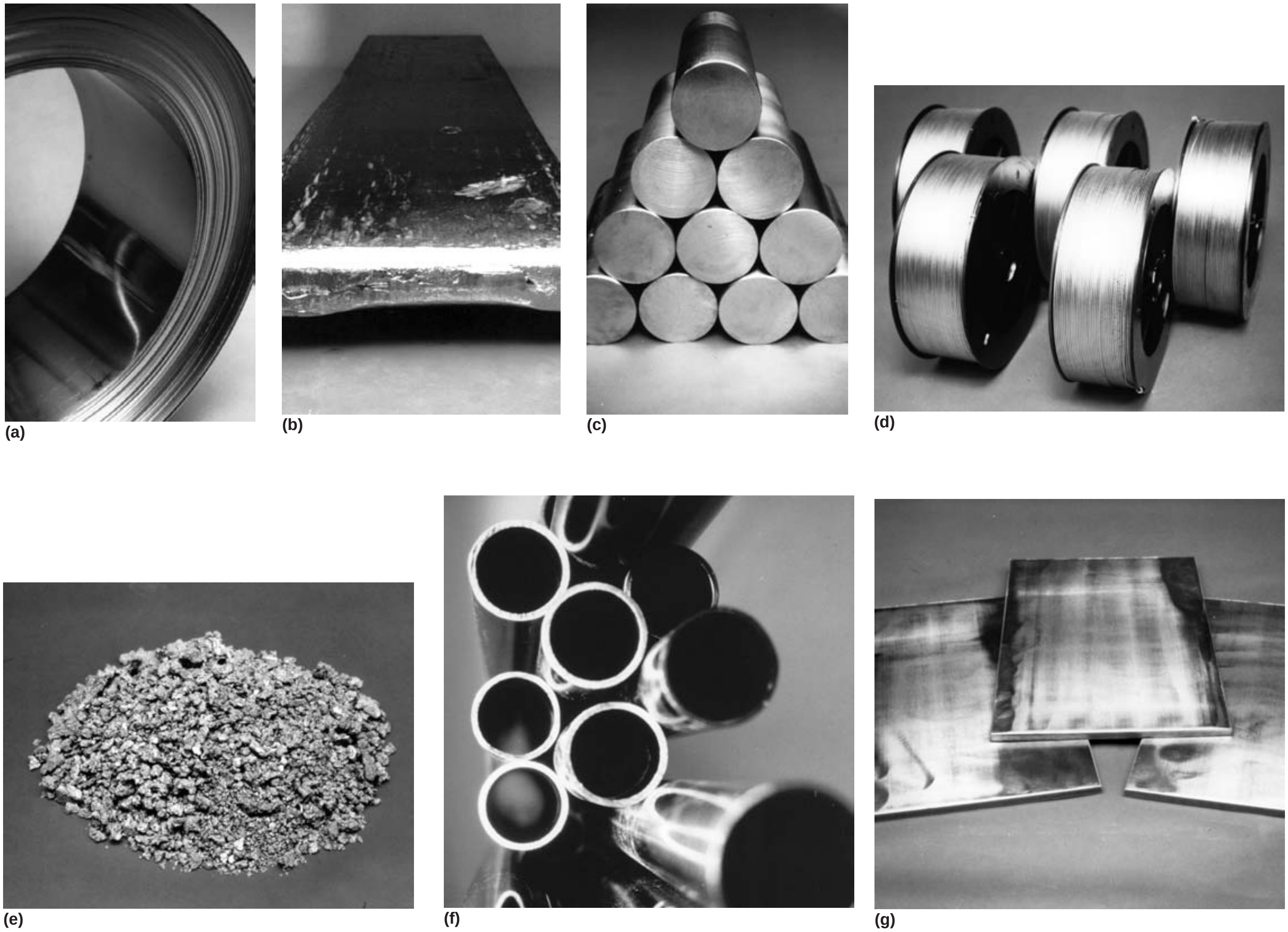


Fig. 2.1 Some titanium and titanium alloys product forms. (a) Strip. (b) Slab. (c) Billet. (d) Wire. (e) Sponge. (f) Tube. (g) Plate. Courtesy of Teledyne Wah Chang Albany

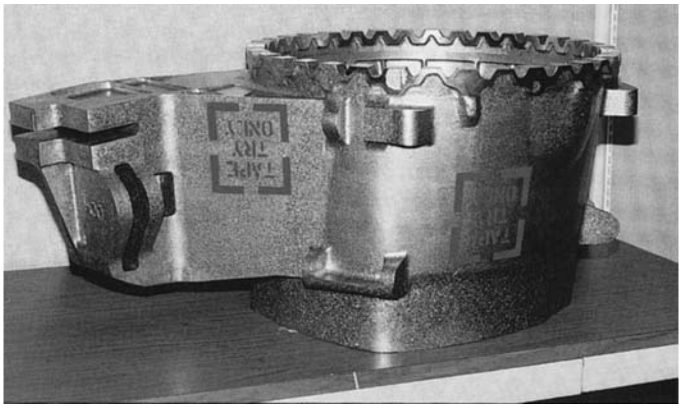


Fig. 2.2 Investment cast titanium transmission case for Osprey vertical take-off and landing aircraft

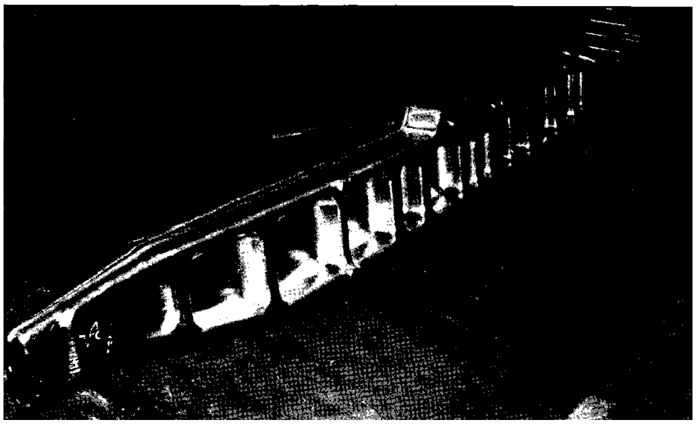


Fig. 2.3 Forged titanium landing gear beam for Boeing 757 aircraft

justify their selection: corrosion-resistant service and strength-efficient structures. For these two diverse areas, selection criteria differ markedly. Corrosion applications normally use lower-strength "unalloyed" titanium mill products fabricated into tanks, heat exchangers, or reactor vessels for chemical-processing, desalination, or power-generation plants. In contrast, high-performance applications such as gas turbines, aircraft structures, drilling equipment, and submersibles, or even applications such as biomedical implants, bicycle frames, and so on, typically use higher-strength titanium alloys. However, this use is in a very selective manner that depends on factors such as thermal environment, loading parameters, corrosion environment, available product forms, fabrication characteristics, and inspection and/or reliability requirements (Fig. 2.4). Alloys for high-performance applications in strength-efficient structures normally are processed to more stringent and costly requirements than "unalloyed" titanium for corrosion service. As examples of use, alloys such as Ti-6Al-4V and Ti-3Al-8V-6Cr-4Mo-4Zr are being used for offshore drilling applications and geothermal piping, while alloys such as Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo+Si, Ti-10V-2Fe-3Al, and Ti-6V-2Sn-2Zr-2Cr-2Mo+Si are used or planned for use in aircraft or in gas turbine engines for aerospace applications.

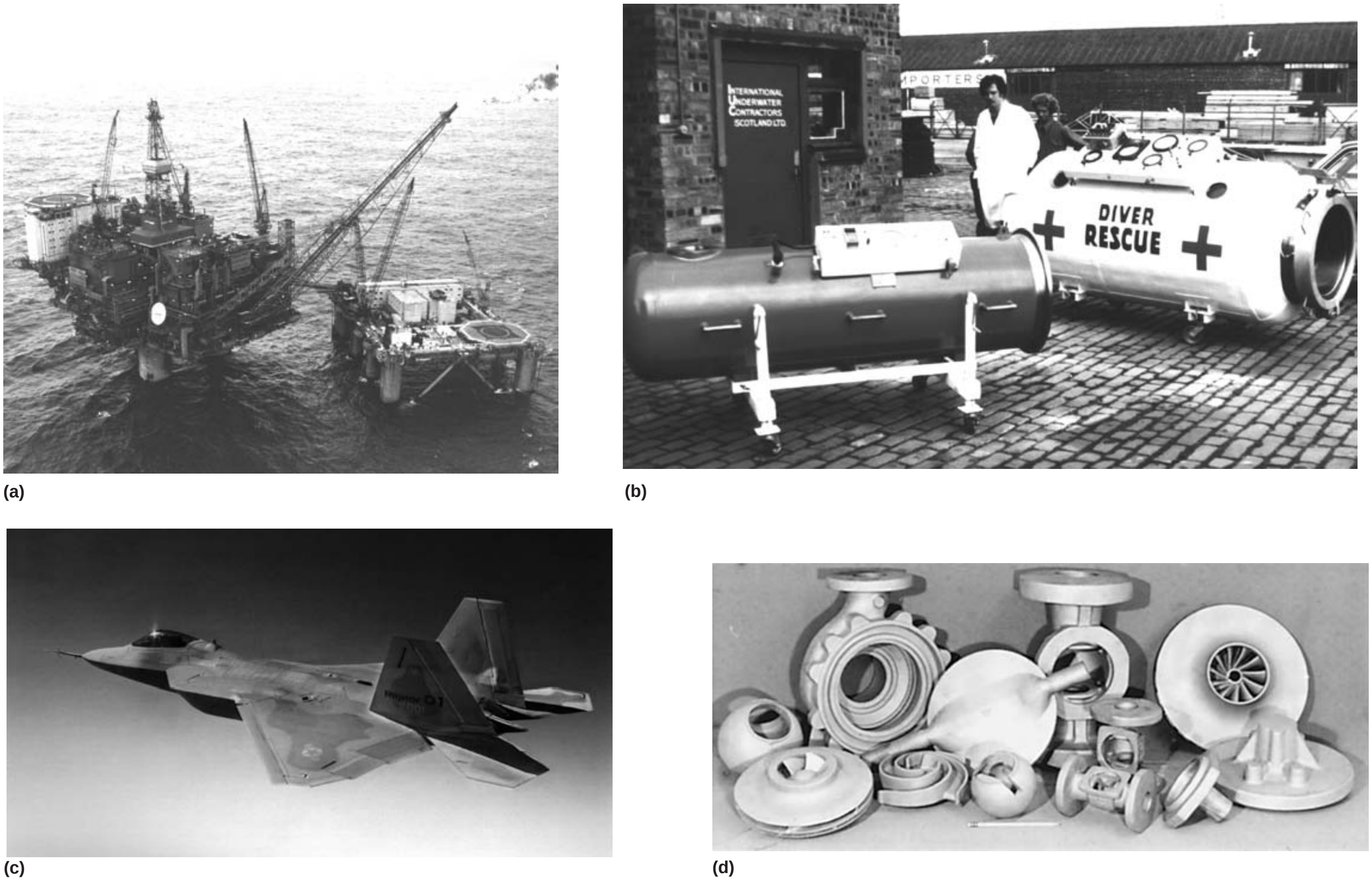
Desired mechanical properties such as yield or ultimate strength to density (strength efficiency), fatigue crack growth rate, and fracture toughness, as well as manufacturing considerations such as welding and forming requirements, are extremely important. These factors normally provide the criteria that determine the alloy composition, structure (alpha, alpha-beta, or beta), heat treatment (some variant of either annealing or solution treating and aging), and level of process control selected or prescribed for structural titanium alloy applications. A summary of some commercial and semicommercial titanium grades and alloys is given in Table 2.2.

For lightly loaded structures, where titanium normally is selected because it offers greater resistance to the effects of temperature than aluminum offers, commercial availability of required mill products, along with ease of fabrication, may dictate selection. Here, one of the grades of unalloyed titanium usually is chosen. In some cases, corrosion resistance, not strength or temperature resistance, may be the major factor in selection of a titanium alloy.

Selection for Corrosion Resistance. Economic considerations normally determine whether titanium alloys will be used for corrosion service. Capital expenditures for titanium equipment generally are higher than for equipment fabricated from competing materials such as stainless steel, brass, bronze, copper nickel, or carbon steel. As a result, titanium equipment must yield lower operating costs, longer life, or reduced maintenance to justify selection, which most frequently is made on a lower total-life-cycle cost basis.

Commercially pure (CP) titanium satisfies the basic requirements for corrosion service. Unalloyed titanium normally is produced to requirements such as those of ASTM standard specifications B 265, B 338, or B 367 in grades 1, 2, 3, and 4 in the United States. These grades vary in oxygen and iron content, which control strength level and corrosion behavior, respectively. For certain corrosion applications, Ti-0.2Pd (ASTM grades 7, 8, and 11) may be preferred over unalloyed grades 1, 2, 3, and 4.

Selection for Strength and Corrosion Resistance. Due to its unique corrosion behavior, titanium is used extensively in prosthetic devices such as heart-valve parts and load-bearing



(a) (b) (c) (d)

Fig. 2.4 A few typical areas of application for high-performance titanium parts. (a) Offshore drilling rig components. (b) Subsea equipment and submersibles requiring ultrastrength. (c) Aircraft. (d) Components for marine and chemical processing operations.

hip and other bone replacements. In general, body fluids are chloride brines that have pH values from 7.4 into the acidic range and also contain a variety of organic acids and other components—media to which titanium is totally immune. Ti-6Al-4V normally is employed for applications requiring higher strength, but other titanium alloys are used as well. Moderately high strength is important in the application of titanium to prosthetics, but strength efficiency (strength to density) is not the prime criterion, assuming that biocompatibility concerns are addressed. However, while strength efficiency is not the defining factor, it has been suggested that the lesser weight of titanium alloy implants plays a noticeable role in patient perception of the efficacy of the device implanted in the body.

Selection for Strength Efficiency. Historically, wrought titanium alloys have been used widely instead of iron or nickel alloys in aerospace applications because titanium saves weight in highly loaded components that operate at low-to-moderately elevated temperatures. Many titanium alloys have been custom designed to have optimum tensile, compressive, and/or creep strength at selected temperatures, and at the same time to have sufficient workability to be fabricated into mill products suitable for a specific application.

Selection for Other Property Reasons. Optic-system support structures are a little-known but very important structural application for titanium. Complex castings are used in surveillance and guidance systems for aircraft and missiles to support the optics where wide temperature variations are encountered in service. The chief reason for selecting titanium for this application is that the thermal-expansion coefficient of titanium most closely matches that of the optics.

Although prosthetic applications for titanium alloys are made for biocompatibility and strength reasons, there is a benefit for structural implants such as hip stems because the lower modulus (than cobalt alloys and stainless) allows more load transfer to the bone and the potential for longer-lasting implant performance.

The Titanium Alloys

For most of the last half of the twentieth century, Ti-6Al-4V accounted for about 45% of the total weight of all titanium alloys shipped. During the life of the titanium industry, various compositions have had transient usage; Ti-4A1-3Mo-1V, Ti-7A1-4Mo, and Ti-8Mn are a few examples. Many alloys have been invented but have never seen significant commercial use. Ti-6Al-4V alloy is unique in that it combines attractive properties with inherent workability (which allows it to be produced in all types of mill products, in both large and small sizes), good shop fabricability (which allows the mill products to be made into complex hardware), and the production experience and commercial availability that lead to reliable and economic usage. Consequently, wrought Ti-6Al-4V became the standard alloy against which other alloys must be compared when selecting a titanium alloy (or custom designing one) for a specific application. Ti-6Al-4V also is the standard alloy selected for castings that must exhibit superior strength. It even has been evaluated in P/M processing. Ti-6Al-4V will continue to be the most-used titanium alloy for many years in the future.

Ti-6Al-4V has temperature limitations that restrict its use to approximately 400 °C (750 °F). For elevated-temperature applications, the

Table 2.2 Some commercial and semicommercial grades and alloys of titanium

	Tensile strength (min)		0.2% yield strength (min)		Impurity limits, wt% (max)					Nominal composition, wt%				
Designation	**MPa**	**ksi**	**MPa**	**ksi**	**N**	**C**	**H**	**Fe**	**O**	**Al**	**Sn**	**Zr**	**Mo**	**Others**
Unalloyed grades														
ASTM grade 1	240	35	170	25	0.03	0.08	0.015	0.20	0.18	…	…	…	…	…
ASTM grade 2	340	50	280	40	0.03	0.08	0.015	0.30	0.25	…	…	…	…	…
ASTM grade 3	450	65	380	55	0.05	0.08	0.015	0.30	0.35	…	…	…	…	…
ASTM grade 4	550	80	480	70	0.05	0.08	0.015	0.50	0.40	…	…	…	…	…
ASTM grade 7	340	50	280	40	0.03	0.08	0.015	0.30	0.25	…	…	…	…	0.2Pd
ASTM grade 11	240	35	170	25	0.03	0.08	0.015	0.20	0.18	…	…	…	…	0.2Pd
α and near-α alloys														
Ti-0.3Mo-0.8Ni	480	70	380	55	0.03	0.10	0.015	0.30	0.25	…	…	…	0.3	0.8Ni
Ti-5Al-2.5Sn	790	115	760	110	0.05	0.08	0.02	0.50	0.20	5	2.5	…	…	…
Ti-5Al-2.5Sn-ELI	690	100	620	90	0.07	0.08	0.0125	0.25	0.12	5	2.5	…	…	…
Ti-8Al-1Mo-1V	900	130	830	120	0.05	0.08	0.015	0.30	0.12	8	…	…	1	1V
Ti-6Al-2Sn-4Zr-2Mo	900	130	830	120	0.05	0.05	0.0125	0.25	0.15	6	2	4	2	0.08Si
Ti-6Al-2Nb-1Ta-0.8Mo	790	115	690	100	0.02	0.03	0.0125	0.12	0.10	6	…	…	1	2Nb, 1Ta
Ti-2.25Al-11Sn-5Zr-1Mo	1000	145	900	130	0.04	0.04	0.008	0.12	0.17	2.25	11	5	1	0.2Si
Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si	1030	149	910	132	0.03	0.08	0.006	0.05	0.15	5.8	4	3.5	0.5	0.7Nb, 0.35Si
α-β alloys														
Ti-6Al-4V(a)	900	130	830	120	0.05	0.10	0.0125	0.30	0.20	6	…	…	…	4V
Ti-6Al-4V-ELI(a)	830	120	760	110	0.05	0.08	0.0125	0.25	0.13	6	…	…	…	4V
Ti-6Al-6V-2Sn(a)	1030	150	970	140	0.04	0.05	0.015	1.0	0.20	6	2	…	…	0.75Cu, 6V
Ti-8Mn(a)	860	125	760	110	0.05	0.08	0.015	0.50	0.20	…	…	…	…	8.0Mn
Ti-7Al-4Mo(a)	1030	150	970	140	0.05	0.10	0.013	0.30	0.20	7.0	…	…	4.0	…
Ti-6Al-2Sn-4Zr-6Mo(b)	1170	170	1100	160	0.04	0.04	0.0125	0.15	0.15	6	2	4	6	…
Ti-5Al-2Sn-2Zr-4Mo-4Cr(b)(c)	1125	163	1055	153	0.04	0.05	0.0125	0.30	0.13	5	2	2	4	4Cr
Ti-6Al-2Sn-2Zr-2Mo-2Cr(c)	1030	150	970	140	0.03	0.05	0.0125	0.25	0.14	5.7	2	2	2	2Cr, 0.25Si
Ti-3Al-2.5V(d)	620	90	520	75	0.015	0.05	0.015	0.30	0.12	3	…	…	…	2.5V
Ti-4Al-4Mo-2Sn-0.5Si	1100	160	960	139	(e)	0.02	0.0125	0.20	(e)	4	2	…	4	0.5Si
β alloys														
Ti-10V-2Fe-3Al(a)(c)	1170	170	1100	160	0.05	0.05	0.015	2.5	0.16	3	…	…	…	10V
Ti-13V-11Cr-3Al(b)	1170	170	1100	160	0.05	0.05	0.025	0.35	0.17	3	…	…	…	11.0Cr, 13.0V
Ti-8Mo-8V-2Fe-3Al(b)(c)	1170	170	1100	160	0.03	0.05	0.015	2.5	0.17	3	…	…	8.0	8.0V
Ti-3Al-8V-6Cr-4Mo-4Zr(a)(c)	900	130	830	120	0.03	0.05	0.20	0.25	0.12	3	…	4	4	6Cr, 8V
Ti-11.5Mo-6Zr-4.5Sn(a)	690	100	620	90	0.05	0.10	0.020	0.35	0.18	…	4.5	6.0	11.5	…
Ti-15V-3Cr-3Al-3Sn	1000(b) 1241(f)	145(b) 180(f)	965(b) 1172(f)	140(b) 170(f)	0.05	0.05	0.015	0.25	0.13	3	3	…	…	15V, 3Cr
Ti-15Mo-3Al-2.7Nb-0.2Si	862	125	793	115	0.05	0.05	0.015	0.25	0.13	3	…	…	15	2.7Nb, 0.2Si

(a) Mechanical properties given for the annealed condition; may be solution treated and aged to increase strength. (b) Mechanical properties given for the solution-treated-and-aged condition; alloy not normally applied in annealed condition. (c) Semicommercial alloy; mechanical properties and composition limits subject to negotiation with suppliers. (d) Primarily a tubing alloy; may be cold drawn to increase strength. (e) Combined $O_2 + 2N_2 = 0.27\%$. (f) Also solution treated and aged using an alternative aging temperature (480 °C, or 900 °F) most commonly used alloy is Ti-6Al-2Sn-4Zr-2Mo + Si. This alloy is primarily used for turbine components and in sheet form for afterburner structures and various "hot" airframe applications. Titanium aluminides may displace the latter alloy but not for commercial applications in the foreseeable future.

During the approximately 50 years that titanium has been commercially available, many other alloys have been developed, but none match the almost 50% market share that Ti-6Al-4V enjoys. In addition to the use of Ti-6Al-4V, Pratt & Whitney has used Ti-8Al-1Mo-1V, Ti-5A1-2.5Sn, Ti-6Al-2Sn-4Zr-2Mo, and Ti-6Al-2Sn-4Zr-6Mo in its gas turbine engines. General Electric has used Ti-4A1-4Mn, Ti-l.5Fe-2.7Cr, and Ti-17 among other alloys in addition to the Ti-6Al-4V alloy. Rolls Royce has used IMI 550, IMI 679, IMI 685, IMI 829, and IMI 834 alloys as well as Ti-6Al-4V (IMI 318) in its engines. (IMI Titanium, Ltd. was a British producer-manufacturer that now operates as Timet UK.) Some of these mentioned alloys have found use in airframes. Other alloys used or evaluated extensively in aerospace, missile and space, and other high-performance applications have included Ti-6V-2Sn-2Zr-2Cr-2Mo + Si, Ti-6Al-6V-2Sn, Ti-10V-2Fe-3A1, and Ti-13V-11Cr-3A1. The latter alloy also is called BI2OVCA. It was the first of a line of metastable beta alloys, although it is now considered somewhat obsolete when compared with most contemporary alloys.

Chemical processing operations have been concerned principally with the unalloyed grades, palladium-containing pure grades, and Ti-6Al-4V. Ti-3A1-8V-6Cr-4Zr-4Mo (also called beta C) was approved for use in deep, sour-well technology. Other alloys are in various stages of use.

The reader may wish to refer to Appendix A ("Summary Table of Titanium Alloys") and/or Appendix B ("Titanium Alloy Datasheets") for more specific information on the types of alloys available and their possible applications.

Application and Control of Titanium Alloys

Rotating components such as jet-engine blades and gas turbine parts require titanium alloys that maximize strength efficiency and metallurgical stability at elevated temperatures. These alloys also must exhibit low creep rates along with predictable behavior with respect to stress rupture and low-cycle fatigue. To reproducibly provide these properties, stringent user requirements are specified to ensure controlled, homogeneous microstructures and total freedom from melting imperfections such as alpha segregation, high-density or low-density tramp inclusions, and unhealed ingot porosity or pipe. The greater the control is, however, the greater the cost will be.

Aerospace pressure vessels similarly require optimized strength efficiency, although at lower temperatures. Required auxiliary properties include weldability and predictable fracture toughness at cryogenic-to-moderately elevated temperatures. To provide this combination of properties, stringent user specifications require controlled microstructures and freedom from melting imperfections. For cryogenic applications, the interstitial elements oxygen, nitrogen, and carbon are carefully controlled to improve ductility and fracture toughness. Alloys with such controlled interstitial element levels are designated ELI (extra-low interstitial), for example, Ti-6Al-4V-ELI.

Aircraft structural applications, along with high-performance automotive and marine applications, also require high-strength efficiency, which normally is achieved by judicious alloy selection combined with close control of mill processing. However, when the design includes redundant structures, when operating environments are not severe, when there are constraints on the fabrication methods that can be used for specific components, or when there are low operational risks, selection of the appropriate alloy and process must take these factors into account.

There are instances of less highly loaded structures in which titanium normally is selected because it offers greater resistance to temperature effects than aluminum does or greater corrosion resistance than brass, bronze, and stainless steel alloys provide. In such cases, commercial availability of required mill products and ease of fabrication customarily dictate selection. Here, one of the grades of unalloyed titanium usually is chosen. Formability (as with tubes) frequently is a characteristic required of this class of applications.

Titanium Alloy Systems Availability

In the United States, 70 to 80% of the demand for titanium was from the aerospace industries during most of the first 50 years that titanium alloys were available commercially. About 20 to 30% was from industrial applications. In the last decade of the twentieth century, demand from nonaerospace industries severely impacted the availability of titanium and its alloys for more traditional high-performance applications at times. For a while, titanium golf clubs were in great demand. Bicycles with titanium frames became quite popular. The golf club market proved to be less durable than expected, and demand is driven by the aerospace applications once again. In view of the fluidity of the market, any speculation or report about titanium application volume would best be gotten from sources such as trade associations, trade journals, or specialized reports prepared by consulting firms.

Several dozen common titanium alloys are readily available. However, as is the case in many industries, there are often significant variations in the specifications to which a given organization purchases, or designs with, titanium alloys. To a large extent, aerospace applications are the prime cause of titanium alloy and process development and, thus, material availability.

The industry has been cyclical in nature and has operated at peak capacity only a few times in the approximately five decades since titanium was introduced as a commercial material. The business conditions of the last decade of the twentieth century led inexorably to a consolidation of the producers of titanium alloys. Further consolidation may be expected in the alloy specifications that govern the use of titanium. Common specification agreements are in the works whereby a single specification may serve as a buying guide for a given composition.

Single specification requirements for a given alloy should not be considered to grant a common design data base for a material, however. Actual design data will continue to be within the purview of titanium users such as gas turbine engine and airframe manufacturers. Commonality of purchasing requirements via common specifications should eventually drive design data to a more common framework. The data provided in this book and most handbooks (examples can be found in Appendix K) are meant to be typical data, not design data.

Evolution of Casting and Precision Forging

While total titanium availability has remained relatively flat for many years, the availability of castings has risen remarkably. In addition to intricate castings, precision forgings, including near-net shape (NNS) forgings, and superplastic forming/forging have shown promise for extending the application of titanium alloys. Figure 2.5 illustrates schematically the areas of titanium usage in an advanced fighter airframe, that of the F-22 Raptor. Only the areas of titanium usage are shown. In the F-22, some 42% of all structural weight will be of titanium. In the aft fuselage alone, almost two-thirds of the weight is titanium.

Titanium castings (Fig. 2.6) represented only 6% of the weight of aircraft gas turbines in the 1980s, but casting usage was expanded in the 1990s, especially when casting vendors moved to reduce costs to engine manufacturers. Powder parts may be available in limited quantities, but they are currently and principally restricted to somewhat more exotic alloys and/or applications.

Titanium usage may increase for advanced gas turbines, but there are not that many new turbines in the works, and there is a tendency to look for "low-cost" materials/components for newer designs. Airframes represent a large-volume application for titanium, and titanium usage for airframes increased steadily through the latter decades of the twentieth century, as seen in Fig. 2.7. Military applications remain the largest volume uses for titanium, and Tables 2.3 and 2.4 show the airframe and/or engine titanium requirements as well as the buy weights for some commercial and military applications.

It was not until about 1965 that nonaerospace usage accounted for a significant fraction of the titanium production. Continued modest growth has been taking place since then in many areas, including biomedical engineering, marine and chemical applications, automotive, and sporting goods. Table 2.5 provides a list of some titanium applications.

The Role of Processing

Titanium alloys are particularly sensitive to the processing conditions that precede their use in service applications. Processing denotes the wrought, cast, or powder methods used to produce the alloy in the appropriate condition for the intended application, as well as the heat treatments that are applied to the alloy. Heat treatment of alpha-beta alloys seems to produce microstructures that are substantially the same as structures produced, for example, by forging the same alloy in the same general temperature region of the phase diagram as that where the heat treatment is carried out. However, the

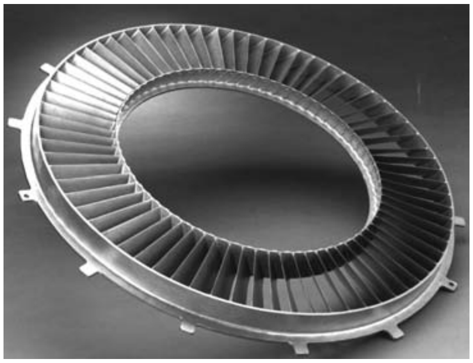


Fig. 2.6 Typical titanium alloy casting for aircraft gas turbine use. Courtesy of Precision Castparts Corp.

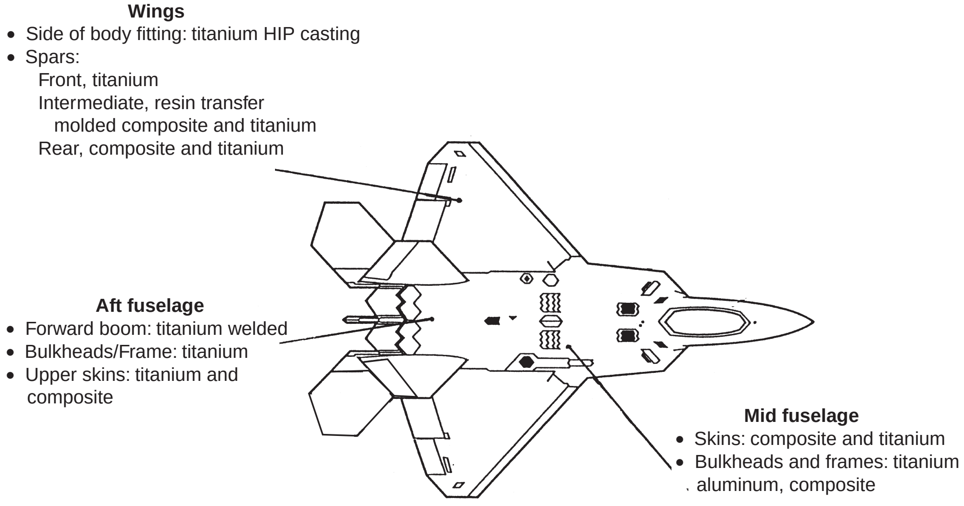


Fig. 2.5 Some areas of titanium use in the F-22 Raptor advanced fighter aircraft

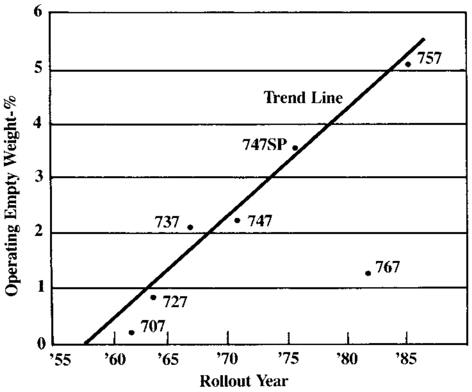


Fig. 2.7 Titanium usage in Boeing aircraft from the first commercial jet to the Boeing 757

Table 2.3 Military aircraft (including engines) titanium requirements

Aircraft/engine(a)	Titanium buy weight kg	Titanium buy weight lb
A-10/(2) TF-34	1,814	4,000
F-5E/(1) J85	635	1,400
F-5G/(1) F404	1,089	2,400
F-14/(2) TF-30	24,630	54,300
F-15/(2) F-100	29,030	64,000
F-16/(1) F-100	3,085	6,800
F-18/(2) F-404	7,620	16,800
C-130/(4) T-56	499	1,100
C-5B/(4) TF-39	24,812	54,700
B-1B/(4)F101-GE-102	90,402	199,300
KG-10/CF-6-50	32,206	71,000
CH-53E/(3) T-64	8,800	19,400
CH-60/(2) T-700	2,041	4,500
S-76/(2) A11.250	544	1,200
AH-64/(2) T-700	635	1,400

(a) Typical uses are A-10 ballistic armament; structural forgings and wing skins for F-14 and F-15 aircraft; rotor parts for helicopter blade systems; B-1B fracture-critical forgings and wing carry-through section; and rotor discs, blades, and compressor cases on various engines.

Table 2.4 Titanium buy weights for commercial and military aircraft

Aircraft/engine(a)	Titanium buy weight kg	Titanium buy weight lb
Fairchild A-10	862	1,900
Northrop F-5	408	900
Grumman F-14	18,870	41,600
McDonnell Douglas F-15	24,494	54,000
General Dynamics F-16	861	1,800
McDonnell Douglas F-18	6,214	13,700
Lockheed C-130	454	1,000
Lockheed C-5B	6,804	15,000
Rockwell B-1B	82,646	182,200
707/(4) JT3	4,445	9,800
727/(3) JT8	4,309	9,500
737-200/(2) JT8	3,810	8,400
737/300/(3) CFM-56	3,810	8,400
747/(4) JT-9	42,593	93,900
757/(2) PW2037	12,746	28,100
757/(2) RB211/535	12,973	28,600
767/(2) JT-9	17,554	38,700
767/(2) CF-6	11,703	25,800
MD-80 (2) JT8-217	6,260	13,800
DC-10/(3) CF-6	32,387	71,400
A300/(2) CF-6	6,350	14,000
A310/(2) CF-6	6,350	14,000

(a) Airframe only; slight variations by specific model. Product forms purchased include sheet, plate, bar, billet, and extrusions.

Table 2.5 Some titanium applications

Aerospace

- Gas turbine engines
- Aircraft structures
- Spacecraft
- Helicopter rotors

Power generation

- Gas turbines
- Steam turbines
- Piping systems
- Heat exchangers
- Flue gas desulphurization systems

Chemical processing industries

- Pressure and reaction vessels
- Heat exchangers
- Pipe and fittings
- Liners
- Tubing
- Pumps
- Condensers
- Valves, ducting, and filters
- Agitators

Automotive

- Body panels
- Connecting rods
- Valves and valve springs
- Rocker arms

Marine

- Surface ship hulls
- Deep-sea submersibles
- Pleasure boat components
- Racing yacht components
- Shipboard cooling systems
- Ship propellers
- Service water systems
- Ducting
- Fire pumps
- Water jet propulsion systems

Fashion and apparel

- Eyeglasses
- Jewelry
- Watches
- Writing instruments

Oil, gas, and petroleum processing

- Tubing and pipe
- Liners
- Springs
- Valves
- Risers

Biomedical

- Artificial joint prostheses
- Bone plates, intramedullary rods, etc.
- Heart valves
- Pacemakers
- Dental implants
- Attachment wire
- Surgical instruments
- Wheelchairs

Architectural

- Roofing
- Window frames
- Eaves and gables
- Railings
- Ventilators

Sports

- Golf clubs
- Bicycle frames, gears, etc.
- Lacrosse sticks
- Racing wheelchairs
- Horseshoes
- Tennis rackets
- Scuba gas cylinders
- Skis
- Pool cues

Miscellaneous

- Shape memory alloys
- Pollution control systems
- Hand tools
- Desalination systems
- Military vehicle armor
- Hunting knives
- Backpack cookware

properties of wrought stock produced by deformation of the alloy at a high temperature generally seem to be better than those produced by heat treatment alone to effect the desired structure. Furthermore, the degree of work placed into the alloy seems to be a controlling factor in the attainment of optimum properties. (Bar stock does not have the same properties as a forged disk.)

Once the alloy composition is selected, the properties of titanium alloys are linked inextricably to the nature of the processing applied to them. One of the more considerable recent processing challenges was to develop satisfactory heat treatment procedures for optimizing the properties and the microstructure of cast titanium alloys after they have been hot isostatically pressed. Heat treatments and fabrication conditions to consolidate titanium powder or to make components from titanium aluminides represent ongoing challenges to the process technology involving titanium.

Property Data

Properties of commercially pure and alloyed titanium may vary from the data presented in Table 2.1. For specific information on many of the commonly used Ti CP grades and alloys, refer to *Materials Properties Handbook: Titanium Alloys*, published by ASM International (Appendix K provides a listing of references for additional information).

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