An Expansive — and Expanding — Scope of Uses

Titanium and its alloys have proven to be technically superior, cost-effective construction materials for a wide variety of aerospace, industrial and commercial applications. In North America, approximately 55% of the titanium manufactured is utilized in aerospace. The recent introduction of composite structures in airframes is increasing the requirements for titanium. Due to the expansion of industrial applications, additional growth is expected to occur in the chemical processing, marine, desalination, medical and architectural sectors. The continued development of newer titanium markets, such as armor/armament and automotive will help drive the titanium industry in this millennium.

Aerospace: Titanium's First and Foremost Application

Titanium's metallurgical and physical characteristics and the requirements of aerospace manufacturers are so congruous that growth of the metal and these industries has been closely intertwined. The aerospace market for titanium includes commercial (and smaller private) aircraft, military aircraft (small fighters, large transports, missiles) and spacecraft.

Selection of titanium or both airframes and engines is based upon its specific properties: weight reduction (due to the high strength-to-weight ratio), coupled with exemplary reliability that is attributable to its outstanding corrosion resistance and mechanical properties.

The Boeing 777 uses nearly 50 tons of titanium, and, the high composite Boeing 787 uses over 100 tons making commercial aerospace the largest single market for the metal.

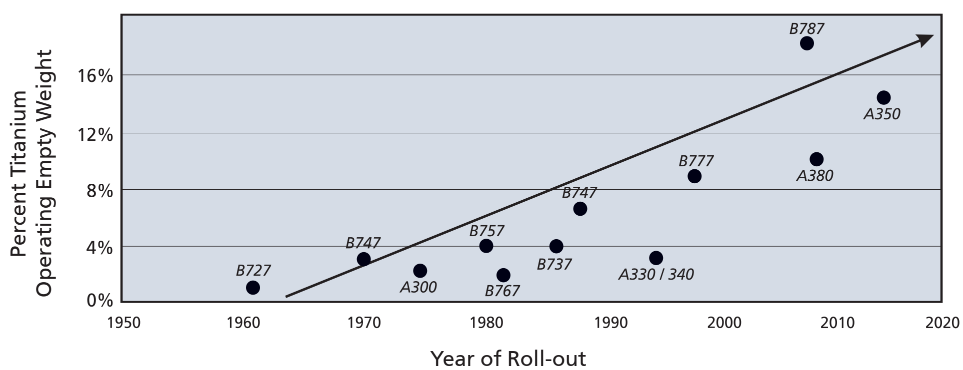
Gas Turbine Engines

Another large user of titanium is in jet engines, where titanium alloy parts make up 25% to 30% of the weight, primarily in the compressor.

These highly efficient engines are possible through the use of titanium alloy components like fan blades, compressor blades, rotors, discs, hubs and numerous non-rotor parts like inlet guide vanes. Titanium is the most common material for engine parts that operate up to 1100°F (593°C), because of its strength and ability to tolerate the moderate tempera-tures in the cooler parts of the engine. Other key advantages of titanium-based alloys include light weight (which translates to fuel economy), and good resistance to creep and fatigue.

Recent advances in titanium production for engines include the use of cold hearth melting to cost-effectively produce ultra clean alloys; the fabrication of titanium wide chord fan blades that increase efficiency and reduce noise; and the casting of large, intricate engine parts and cases that reduce assembly time.

The percentage of titanium used in aircraft increases with each design generation. In military craft, today's F-15 is 26% titanium, compared to the 1960's F4, which was 9% titanium by weight. The more recent F-22 contains 39% titanium by weight. (The military's SR-71 was 90% titanium and still holds all speed and altitude records.) In commercial craft, not only is there a greater percentage of titanium being used per plane, but also larger planes require a greater total amount of titanium.



Titanium Usage on Boeing Aircraft

Source: Boeing Commercial Airplane Group

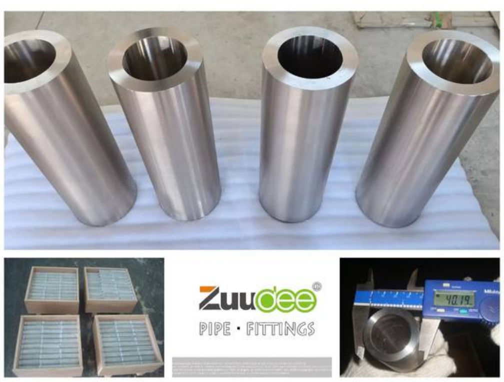
Airframes

Titanium alloys effectively compete with aluminum, nickel and ferrous alloys in both commercial and military airframes. Applications run the gamut of airframe structural members— from massive, highly stressed, forged wing structures, to critical small fasteners, springs and hydraulic tubing.

Titanium alloys now replace nickel and steel alloys in nacelles and landing gear components in newer airframes such as the Boeing 777, 787 and Airbus 380. Investment casting techniques allow complex shapes to be made at relatively low cost. (For example, heat shields that protect wing components from engine exhaust are cast of titanium.) Cold hearth melting excels at producing defect-free metal for critical rotating engine components. Superplastic forming/diffusion bonding has helped to increase the use of titanium alloys in new airframe designs, by lowering the cost through less machining, reworking and fewer component parts.

Space Structures

Starting with the extensive use of titanium in the early Mercury and Apollo spacecraft, titanium alloys have been widely used in military and NASA space applications. The Space Shuttle uses titanium alloys for diffusion-bonded members in the thrust structure, as well as for pressure vessels, hydraulic tubing and the vertical stabilizer. In addition to manned spacecraft, titanium alloys are extensively employed in solid rocket booster cases, guidance



control pressure vessels and a wide variety of applications demanding lightweight and reliability.

Thick Section Titanium

Thick section size in aerospace is generally defined as forged or rolled product with a thickness that exceeds four inches. Titanium alloys offer a useful, and in many cases superior, alternative to steel alloys for thick section application. They demonstrate superior fatigue and fracture toughness properties, both in the absolute sense and from the standpoint of uniformity throughout the section thickness, even as thickness increases from 4" to 6" to 8". Thick section titanium alloys have been successfully used in airframe parts and in rotating components such as fan disks for PWA and GE high bypass jet engines and Sikorsky helicopter rotor forgings.

Industry: Suitability For a Wide Array of Applications

Titanium's utility in industry is primarily due to its exceptional corrosion resistance, which allows designers to specify it with no corrosion allowance and allows plants to reduce maintenance to improve life cycle costing. Commercially pure (CP) grades are the most often used, with CP Grade 2 by far the most common in industrial applications.

Heat Exchangers

Titanium's properties, in particular its virtual immunity to corrosion in salt, brackish or polluted waters, lead to extremely reliable, highly efficient, cost competitive heat exchangers. Not only are initial costs for titanium attractive relative to other metals, but also life cycle costs are lower because maintenance is reduced. Titanium is readily available in welded and seamless tubing in many alloy grades for shell/tube exchangers, or in pressed form for plate and frame exchangers.

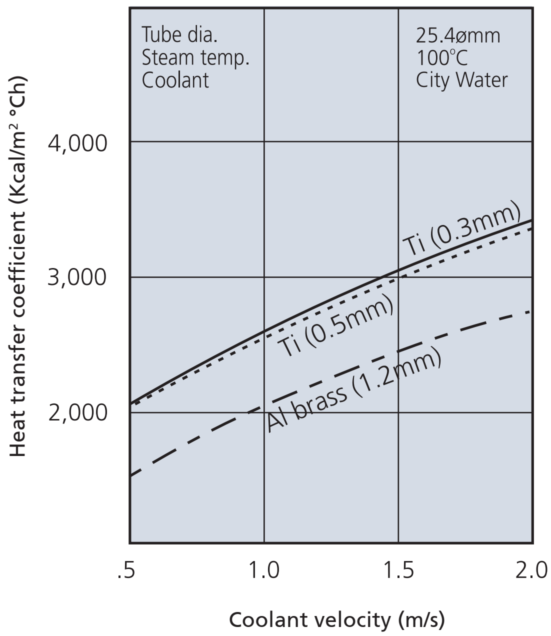
In power plants, refineries, air conditioning systems, chemical plants, offshore platforms, surface ships and submarines, titanium's lifespan and dependability are proven. In fact, with over 300 million feet of welded titanium tubing in power plant condenser service, there have been no reported failures due to corrosion.

Based on its outstanding natural resistance to corrosion and erosion-corrosion, titanium can be specified for heat transfer tubing with a zero corrosion allowance, which, with its good strength, permits use of very thin walls. This reduces exchanger size, weight and material requirements and minimizes total cost. In fact, titanium can be comparable in initial cost to certain copper or stainless steel alloys.

Thinner walls coupled with its surface characteristics promote excellent heat transfer. Titanium's hard, smooth surface accepts very high fluid flow rates and minimizes buildup of external fouling films which can rob metals of heat transfer efficiency. Although copper-based alloys possess higher thermal conductivity and overall heat transfer coefficients when new and clean, titanium exhibits higher long-term operating coefficients in actual service.

It is not unusual to observe a 95-100% cleanliness factor for titanium in many services. Although it's not biotoxic, biofouling can be successfully controlled by periodic chlorination and/or mechanical means ("bullets," tube brushes and sponge balls). A fouling factor of 0.0005 is easily achieved for titanium in seawater using these strategies.

Heat Transfer Rate of Tubes used in a Model Condenser for Six Months



Source: Japan Titanium Society

Titanium is also unique in its ability to promote drop wise condensation on its surface. Most metals form continuous surface films of condensate when condensing water vapor in evaporative processes. This is not nearly as efficient as titanium's drop wise mechanism for brine and nitric acid distillation.

Power Generation

Steam turbine failure has historically accounted for over 30% of the downtime of power plants. The use of Ti-6Al-4V for turbine blades in critical areas increases the efficiency and life of low-pressure steam turbines while decreasing downtime and maintenance. CP titanium thin-wall condenser tubing is used extensively in power plants, because it can be specified without a corrosion allowance and has a virtually unlimited life, well past the life of the condenser or plant. In nuclear power stations, the availability and declining cost of seam welded titanium tubing has led to an increase in its use.

Chemical Processing

In many corrosive process environments, titanium proves to be the most economical solution. Its natural corrosion resistance helps maximize equipment life, reduce downtime and improve overall plant performance. Hearth melting is now used to economically produce high quality titanium from nearly any mix of raw material and titanium scrap. Fabrication and welding are well understood. Today, the upfront cost of the metal and its fabrication are highly competitive with other materials, and lifecycle costing often gives titanium the edge in a cost/performance analysis. It is commonly used for heat exchangers, vessels, tanks, agitators and piping systems in the processing of aggressive acidic compounds, as well as inhibited reducing acids and hydrogen sulfide.

Offshore Oil and Gas

Titanium's seawater corrosion resistance, lightweight, high strength and low modulus make it ideal for a variety of applications in offshore oil and gas exploration and production. Topside, titanium tubing and pipe is used extensively in fire main and service water systems, because it eliminates difficult, expensive offshore maintenance, repairs and replacement. Its high strength-to-weight ratio and low modulus make it well suited for dynamic production and drilling riser systems, where every pound of weight saved below the surface also saves three to five pounds on the platform and anchoring system. High operating pressures, temperatures, and sour environments also favor titanium risers over traditional metallic/rubber composites. With its low modulus, titanium is also used for stress joints, to accommodate platform movement. Because titanium is non-magnetic and seawater corrosion immune, it is ideal for seismic array and downhole well logging components. As deeper reservoirs are explored and higher temperature oil and gas are recovered, titanium's role offshore should continue to expand, and the industry has the capacity and fabrication capabilities to meet the demand.

Downhole Oil and Gas

In deep sour gas well applications, the exceptional resistance of titanium alloys to attack from H_2S, CO_2, and chloride-rich brines, combined with high strength and low density, make them especially attractive for applications such as packers, tubing strings, liners, safety valves and springs. Numerous titanium alloys are approved for sour service under the NACE MR-01-75 standard for sour brine service temperatures in excess of 250°C.

Petroleum Processing

The need for longer equipment life, coupled with requirements for reduced downtime and maintenance, favor the use of titanium in heat exchangers, vessels, columns and piping systems in refineries and liquid natural gas plants. It is immune to general attack and stress corrosion cracking from hydrocarbons, H_2S, CO_2, ammonia and chloride brines.

Marine Applications

Titanium provides an ideal solution to the problems that have traditionally characterized seawater applications. It is unsurpassed in corrosion immunity for marine service and is not subject to pitting, crevice corrosion, stress corrosion cracking or microbiologically influenced corrosion in natural seawater. Coupled with its low density, high strength and erosion resistance, this means unexcelled performance in terms of service life, weight savings and reduced maintenance costs for the marine design engineer. In fact, titanium performs so well that producers can offer warranties as long as100 years in certain seawater applications.

Beyond its metallurgical characteristics, its availability, low life cycle cost and ease of fabrication make titanium a prime candidate for ship propellers, shipboard heat exchangers, piping systems, and ballast, waste, drain and sprinkling systems. It is also being used on everything from ferries and fishing boats, to naval ships, deep-sea submersibles and submarines. A titanium commercial ship hull has been built and tested, and although its initial cost is higher than a conventional hull, its long life, lower maintenance costs, and reduced fuel consumption could make it more cost-effective over the life of the ship.

Desalination

Excellent resistance to corrosion/erosion and high condensation efficiency make titanium the most dependable material for critical segments of multi-stage evaporation desalination plants. Because welded titanium condenser tubing can be thin-walled, it is cost-competitive with copper-nickel, which it far surpasses in life. It is also used in the rejection, heat recovery and heat input stages.

Armor/Armament

The application of titanium in ballistic armor is focused on two areas: armored vehicles and ordnance, and personal armor. On tanks and ground vehicles, titanium reduces weight to enhance airlift transportability and fighting force mobility. In comparison to traditional rolled homogenous armor, titanium offers an excellent strength-to-weight ratio, good ballistic properties and multi-hit capacity, corrosion resistance and

weldability /machinability. In addition to hull armor, titanium is used for turrets, hatches and suspensions, which, when made of steel, can account for over 50% of a tank's weight. Titanium is also being used in field guns, notably the Ultralightweight Field Howitzer (UFH) where helicopter, transporter aircraft and ship can transport its 3,745kg weight.

Metal Recovery and Finishing

Hydrometallurgical extraction of metals such as nickel from ores in titanium reactors is an environmentally safe alternative to smelting. Extended lifespan, increased energy efficiency and greater product purity are promoting the use of titanium electrodes in electro-winning and electro-refining of metals like copper, gold, manganese and manganese dioxide.

Chlor-Alkali Processing

The unique electrochemical properties of titanium make it the most energy efficient choice for dimensional stable anodes (DSA's) used for the production of chlorine, chlorate and hypochlorite.

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Pulp and Paper

Due to the recycling of waste fluids and the need for greater equipment reliability and lifespan, titanium has become the standard material for drum washers, diffusion bleach washers, pumps, piping systems and heat exchangers in the bleaching section of pulp and paper plants. This is particularly true for equipment developed for chlorine dioxide bleaching systems.

Flue Gas Desulphurization

Laboratory studies and field experience have proven titanium has exceptional corrosion/erosion resistance in scrubber systems, ducting and stacks used to remove pollutants from waste gases. Its long life makes it a prime candidate for pollution control systems.

Food and Pharmaceutical

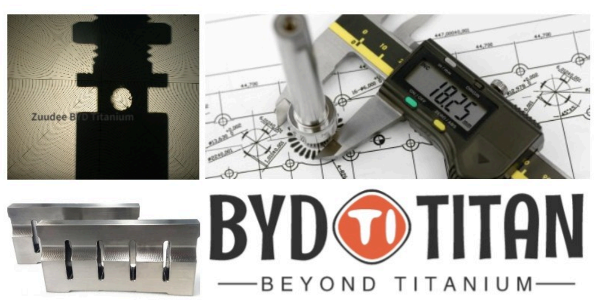
Titanium demonstrates excellent corrosion resistance, not only to various food products and pharmaceutical chemicals, but also to the cleaning agents utilized. As equipment life becomes a more critical factor in financial evaluations, titanium equipment is replacing existing stainless steel apparatus. Titanium can also eliminate the problems of metal contamination.

Nuclear Waste Storage

Nuclear waste must be stored safely for hundreds of thousands of years. Titanium's proven resistance to attack from naturally occurring geologic fluids, as well as its extremely short half-life, makes it a prime candidate for multi-barrier disposal systems.

High Technology

Titanium's temperature and corrosion resistance and strength have created a major role for the metal in such applications as sputter targets (for integrated circuits); super-conducting alloys (50%Nb - 50%Ti used in electromagnets and energy storage and transmission); shape memory alloys (50%Ni – 50%Ti used in spring coils in solenoids and linear motors); computers (hard drive substrates); and optical systems.



Metal Matrix Composites

Titanium is being researched as a matrix material for industrial, and potentially, aerospace applications. While offering an elevated-temperature resistant, ductile base, titanium can be further strengthened with the addition of ceramic or intermetallic compounds in fiber or particulate form to produce properties beyond those achieved by alloying alone. Current developments using SiC fiber reinforcements could permit titanium base composites to replace nickel and steel alloys in higher temperature and higher modulus applications.

Titanium Aluminides

This class of materials, typically with titanium-aluminum ratios of 1:1 to 1:3, represents the next generation of alloys intended to push the applications of titanium beyond the traditional 1100°F barrier. Two types of aluminides are currently under investigation. The alpha 2 aluminide, typified by the Ti_3Al intermetallic compound, shows potential in gas turbine engines; the gamma aluminides, represented by the TiAl formula, are the research material of choice for all other applications. Variations of both types, containing a variety of alloying elements, are being studied to overcome the inherent low ductility and fabricability of these compounds, which have prevented significant applications.

Ferro-Titanium

The low quality portion of available titanium scrap is recycled to make ferrotitanium, which is mainly used as an microalloy additive to steel and stainless steel. Ti acts as a "getter" to tie up unwanted interstitial elements (oxygen, nitrogen, carbon, and sulfur) for improved ductility and formability. In ferritic carbon steels, it is also used for the production of high strength low alloy (HSLA) steels using the strengthening effect of TiC precipitation in the ferrite. Total Ti additions may range from 0.005% to 0.15% by weight.

Other Industrial Applications

These include anodes for cathodic protection (used to prevent corrosion of other metals); electro-chemical processes (such as electro-plating and anodizing); deep drilling (as in geothermal energy exploration); hand tools; tool and machinery coatings (to enhance high speed performance and extend life); and heating elements. $TiCl_4$ is also used as an active ingredient in the catalysis of high density and linear low density polyethylene according to the Sclairtech process.

Commercial and Consumer: Adding Value in Hundreds of Common Uses

A combination of factors is expanding the traditional uses for titanium to encompass a wider and wider range of applications. The titanium industry has done extensive missionary work, increased capacity to meet growing demand and there is a better understanding of how to work with the metal.

Sporting Goods

One of the first and most visible consumer uses of the metal was in titanium golf clubs. Because it is light and strong, club heads from titanium can be bigger, affording a larger "sweet spot" to improve distance and accuracy.

The Ti-3Al-2.5V alloy has cost-effectively demonstrated the properties needed for other successful sports applications: good strength-to-weight ratio, low modulus of elasticity and excellent dampening characteristics. For these reasons, bicycle frames and parts, tennis racquet frames, skis, pool cue shafts and baseball bats are all currently being fabricated from the metal. Lacrosse sticks and snowshoes are also made of titanium.

Consumer Goods

Titanium's inherent beauty and unique blend of physical properties make it a natural choice for many consumer uses, including jewelry, wrist watches, eyeglass frames, wedding rings, camera bodies, and even loudspeakers and non-stick coatings.

Medicine

With complete resistance to attack by body fluids, plus high strength and low modulus, titanium is the most biocompatible of all metals. It was first used in surgery in the 1950'sand now is widely used for human prosthetic and replacement devices (hip replacements, expandable rib cages, spinal implants, etc.) Titanium will actually allow bone growth to adhere to the implants, so they last longer than those made of other materials. Reconstructive titanium plates and mesh that support broken bones are also commonly used today. Pace-maker cases and artificial heart valves are being fabricated from titanium, as are dental fixtures (replacement teeth, crowns, braces, etc.). Durability and lightweight have led to its use in wheelchairs. The metal is also widely used to fabricate surgical devices and centrifuges.

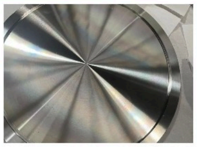
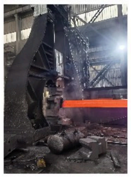
Architecture/Construction

As a building material, titanium out performs every other architectural metal and is gaining rapid acceptance. Due to its mechanical and physical properties, corrosion resistance and attractive appearance, it is used for exterior cladding, roofs, fascia, canopies and dozens of other building purposes. It is also used in outdoor art and sculptures, for its weather resistance and striking beauty. Because it is totally immune to corrosion in all environments, including marine and industrial, it is a highly practical choice when life cycle and maintenance costs are considered. Commercially pure titanium, ASTM Grade 1, is most often specified for architectural applications.

Automotive

With the sheer size of the world automotive market, even a small amount of titanium in every car would create a huge demand for the metal. Because cost is a major factor in passenger vehicles, the industry's emphasis has been on developing low cost titanium products. Designs that exploit titanium's unique characteristics can yield parts that more than pay for themselves with better performance and a longer life. Factors such as fuel economy, emissions legislation and longer warranties are compelling automotive engineers to consider titanium as a "value engineering" solution.




In commercial engines, evaluations have demonstrated that titanium valve trains can improve fuel efficiency by 4% and they are being evaluated in several engines. Suspension springs, engine springs, exhaust systems and brake pads are all being investigated. Small quantities of titanium are being used in high-end cars such as a muffler on the Corvette and springs on a VW model.

Effort is also being placed in the racing market. Titanium is now used for high performance vehicle components such as valves, valve springs, rocker arms, connecting rods and frames, due to its high strength, low weight and corrosion resistance. Titanium was used in recent years for the fuselage skin of a test vehicle that broke the world land speed record. The automotive and motorcycle after markets are also active.