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TITANIUM

**The
ULTIMATE
Choice**

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Titanium — Coming of Age

Titanium, once considered an exotic, expensive metal suited exclusively to aerospace use, has come of age as a versatile metal for numerous everyday applications, due to its unique metallurgical properties, abundant availability, low life cycle cost and ease of fabrication. It is now commonplace not only in aircraft, but in industries including chemical and petrochemical processing, offshore oil and gas, marine and desalination, as well as in commercial and consumer uses ranging from golf clubs to medical implants and architecture.

Examining the Benefits

Why are engineers, purchasing managers, fabricators, maintenance directors, and management turning to titanium to address their myriad design, performance and financial challenges? There are four related reasons to consider the metal and its alloys for any given application:

Maximum Performance

Many items, such as jet engine fan blades and medical implants, simply perform best when manufactured of titanium, due to the metal's unique combination of mechanical and physical properties.

Performance-to-Cost

In some cases, titanium enhances an item's performance so dramatically it is worth a higher cost than another material. For example, recreational products like golf clubs offer a playing experience that's worth a higher price; on an automobile, titanium connecting rods save enough weight to improve performance without adding a costly turbocharger.

Life Cycle Cost

In chemical processing and marine environments, for example, the initial higher cost of titanium pipe, fittings and tubing can be regained several fold by the savings that result from its long (many times unlimited) life and a corresponding reduction in equipment maintenance and process downtime.

Total Design

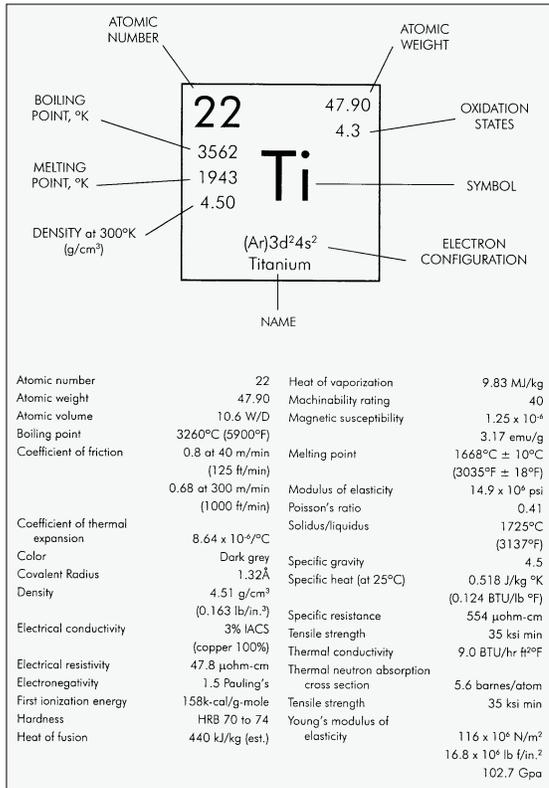
In some situations, the use of titanium can allow other parts of the complete system to be built more simply and cheaply. For example, on semi-submersible oil and gas offshore platforms, lighter weight titanium riser pipe can substantially reduce the required size and weight of platform structure, riser interface and peripheral components, thereby reducing the overall project cost.

In each case, it is a combination of titanium's physical characteristics, such as strength, light weight and corrosion resistance, that imparts a synergy of benefits to the end application. Furthermore, a natural abundance of the ore and new, more efficient production methods have made titanium more consistently available and affordable than ever before.



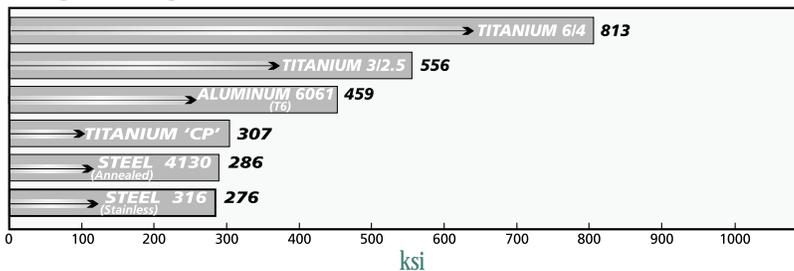
A Unique Set of Characteristics Creates Intrinsic Value

Titanium's accelerating usage is attributable to its remarkable and distinctive combination of physical and metallurgical properties. The key to best utilizing titanium is to exploit these characteristics, especially as they complement one another in a given application, rather than to just directly substitute titanium for another metal.



Exceptional Strength-to-Weight Ratio
Titanium's excellent tensile and yield strength combined with its low density results in the highest strength-to-weight ratio of any of today's structural metals. Especially when it is alloyed, titanium is as strong as steel, yet its specific gravity is only 56% that of steel. This is a prime advantage for its use in aerospace, of course, and also for such diverse applications as deepwell tubing strings and offshore risers in the petroleum industry, surgical implants, and golf club heads.

Strength-to-Weight Ratios of Structural Metals



Source: International Titanium Association (ITA)

Titanium's yield strengths range from 25,000 psi (172 MPa) for commercially pure (CP) Grade 1 to above 200,000 psi (1380 MPa) for heat treated beta alloys. The densities of titanium-based alloys range between .160 lb/in³ (4.43 g/cm³) and .175 lb/in³ (4.85 g/cm³).

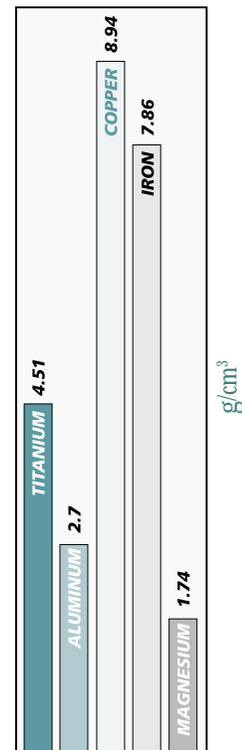
Low Density

Titanium's low density, roughly 56% that of stainless steels and half that of copper and nickel alloys, means greater metal volume per pound compared to other materials.

In conjunction with its strength, this often means components can be made smaller and/or lighter. This is the basis for many aerospace applications, and also for rotating or reciprocating components such as centrifuges, pumps and automotive valves and connecting rods.

Titanium's low density, combined with its natural corrosion resistance, also gives it advantages over other materials in aggressive environments. Based on its strength and the fact it needs no corrosion allowance, it can be specified in thinner cross-sections, using less metal per unit of area. On a dimensional or per-piece basis, this effectively offsets its higher per-pound cost, especially when life cycle costs are also considered. Based on this, downhole oil and geothermal well production tubulars and logging tools are being produced from titanium alloys. In marine service, pleasure boat components, naval surface ships and submarine cooling water systems are growing markets for titanium, driven by its light weight and immunity to seawater corrosion.

Densities of Various Metals



Source: ITA

Excellent, Natural Corrosion Resistance

Titanium is a reactive metal, meaning it spontaneously forms a natural oxide film (mainly TiO_2) in the presence of any oxygen. Whenever there is any amount of air or water in a process stream or environment, the oxide film forms and protects the metal from corrosive attack. If the film is scratched or damaged, it repairs itself instantly. The highly-adherent film is exceptionally resistant to a broad range of acids and alkalis, as well as natural, salt and polluted waters. Titanium's corrosion resistance together with its low density, high strength and erosion resistance, make it ideal for numerous chemical processing and marine uses, as well as architectural applications.



Corrosive Environments Where Titanium's Oxide Film Provides Resistance

Chlorine and Other Halides

- Fully resistant to moist chlorine and its compounds.
- Fully resistant to solutions of chlorites, hypochlorites, perchlorates and chlorine dioxide.
- Resistance to moist bromine gas, iodine and their compounds is similar to chlorine resistance.

Water

- Immune to corrosion in all natural, sea, brackish and polluted waters.
- Immune to Microbiologically Influenced Corrosion (MIC).

Oxidizing Mineral Acids

- Highly resistant to nitric, chromic, perchloric and hypochlorous (wet chlorine gas) acids.

Gases

- Corrosion resistant to sulfur dioxide, ammonium, carbon dioxide, carbon monoxide, hydrogen sulfide and nitrogen.

Inorganic Salt Solutions

- Highly resistant to chlorides of sodium, potassium, magnesium, calcium, copper, iron, ammonia, manganese and nickel.
- Highly resistant to bromide salts.
- Highly resistant to sulfides, sulfates, carbonates, nitrates, chlorates and hypochlorites.

Organic Acids

- Generally very resistant to acetic, terephthalic, adipic, citric, formic, lactic, stearic, tartaric and tannic acids.

Organic Chemicals

- Corrosion resistant in organic process streams of alcohols, aldehydes, esters, ketones and hydrocarbons, with air or moisture.

Alkaline Media

- Low corrosion rates in hydroxides of sodium, potassium, calcium, magnesium and ammonia.

Information provided as an overview. Before specifying titanium in any aggressive environment, consult corrosion experts. Adapted from "Shedding New Light on Titanium in CPI Construction," by James S. Grauman and Brent Willey, Chemical Engineering, August 1998.

Superior Erosion Resistance

Titanium's oxide film also provides superior resistance to abrasion, erosion, erosion-corrosion, cavitation and impingement attack in high velocity process streams. It is up to twenty times more erosion resistant than copper-nickel alloys.

Erosion-Corrosion Resistance to Seawater

Seawater Flow Rate (m/sec)	Duration (Months)	Corrosion Rate - (mm/yr)	
		Gr 2 Ti	70-30 Cu Ni
0.6 - 1.3	6	1.0×10^{-7}	0.02
1.0	54	7.5×10^{-4}	—
7.2	1	5.0×10^{-4}	0.12
8.5	2	1.2×10^{-4}	0.05
9.0	2	2.8×10^{-4}	2.1
9.10	2	1.8×10^{-4}	—
9.8	12	<0.0025	0.3

Source: ITA

In contrast to piping and heat exchangers made from copper-based alloys, equipment made from titanium can be designed for high flow velocities without detrimental effects from turbulence, impingement or cavitation. This erosion/corrosion resistance combined with low density has made titanium alloys prime materials for fluid flow components in chemical and power plants and marine/naval applications. Titanium optimizes heat transfer efficiency, minimizes tube/piping size and wall thickness requirements, improves equipment reliability and reduces life cycle costs. Applications are as diverse as ship superstructures, service water, firemain and weapons systems, exhaust uptakes, launch systems, jet blast deflectors and ventilation ducting.

High Operational Thermal Conductivity

Under in-service conditions, titanium's heat transfer efficiency approximates that of admiralty brass and copper-nickel, and surpasses that of stainless steel. Titanium's higher strength permits the use of thinner walled pipe, tubing and equipment; the oxide film keeps the surface bright, smooth and resistant to higher fluid flow velocities.

Low Modulus of Elasticity

Titanium's low modulus means excellent flexibility and strong springback characteristics. This promotes its use in various springs for aircraft and valves, where a modulus half that of steel, but a strength equivalent to steel allows a titanium spring to be half as large and heavy. This property also benefits auto parts

(which must absorb shock), medical implants (that must move with the body), architecture (where roofs must resist hail), and recreational gear (golf clubs, tennis racquets, mountain bikes and skis).

Low Coefficient of Expansion

Titanium's coefficient of expansion is significantly less than ferrous alloys, copper-nickel alloys, brass and many stainless steels, making it much more compatible with ceramic and glass materials than most metals. This contributes to its architectural utility, particularly when metal-to-ceramic/glass seals are involved.

Non-Magnetic

Titanium is virtually non-magnetic, making it ideal for applications where electro-magnetic interference must be minimized, such as electronic equipment housing and downhole well logging tools. It also contributes to titanium's role in human body implants, where a magnetic metal could be subject to outside interference.

Biocompatible

Titanium is non-allergenic and non-toxic to living tissues. Together with its natural resistance to bodily fluids and low modulus, as well as non-magnetic properties, this makes titanium the most biocompatible of all metals, and leads to its use for prosthetics and implants.

Extremely Short Half-Life

In contrast to many ferrous alloys, titanium alloys do not contain a significant amount of elements which may become radioactive for long periods of time. This permits the use of titanium in nuclear systems.

Dramatic Appearance

Titanium's distinctive, striking beauty results from its oxide film, which absorbs, refracts and reflects light, creating interference that gives titanium its color. The film thickness can be increased by anodic oxidation to vary the color. The metal's surface texture can also be varied. These traits enhance titanium's value in architecture, jewelry and even bicycles.

Environmentally Friendly

Titanium is made from an abundant natural resource which is mined with minimal impact. Its production generates no harmful by-products and 95% of its scrap can be recycled into titanium or ferro-titanium products.

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 60% of the titanium manufactured is utilized in aerospace. Due to the expansion of existing industrial applications, the greatest 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 the new 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 for 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.

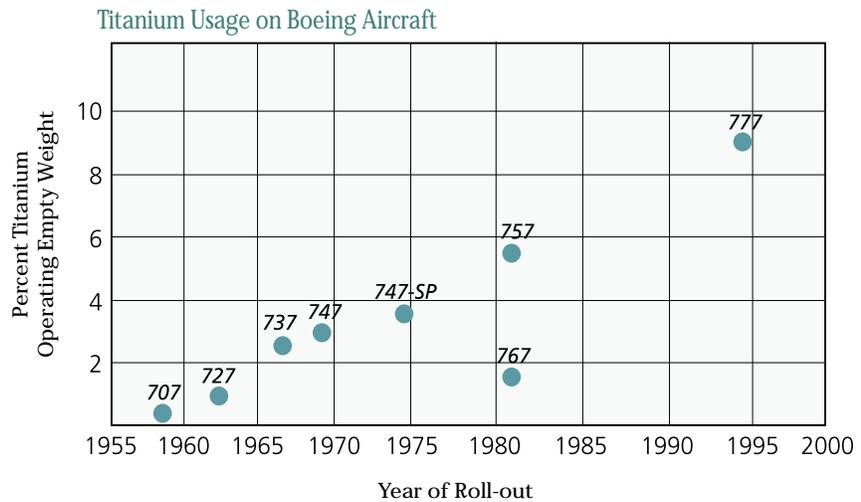
The percentage of titanium used in aircraft increases with each design generation. In military craft, today's F-15 is 26% titanium, compared to the 1960's F4, which was 9% titanium by weight. The F-22 design calls for 39% titanium by weight. (The military's SR-71 was made 90% from titanium and still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

The Boeing 777 uses nearly 50 tons of titanium, and, of course, many more of these will be built than any military aircraft.

Gas Turbine Engines

The largest single use of titanium is in jet engines, where titanium alloy parts make up 20% 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 temperatures 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. The development of titanium aluminides should allow the use of titanium in hotter sections of a new generation of engines.



Source: Boeing Commercial Airplane Group

Recent advances in titanium production for engines include the use of cold hearth melting to cost-effectively produce ultraclean 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.

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 the Boeing 777. 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 clean metal for structural applications while controlling costs. Superplastic forming/diffusion bonding and powder metallurgy have helped to increase the use of titanium alloys in new airframe designs, by lowering the cost of machining and the amount of waste.

Space Structures

Starting with the extensive use of titanium in the early Mercury and Apollo space craft, 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 space craft, titanium alloys are extensively employed in solid rocket booster cases, guidance control pressure vessels and a wide variety of applications demanding light weight 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 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.

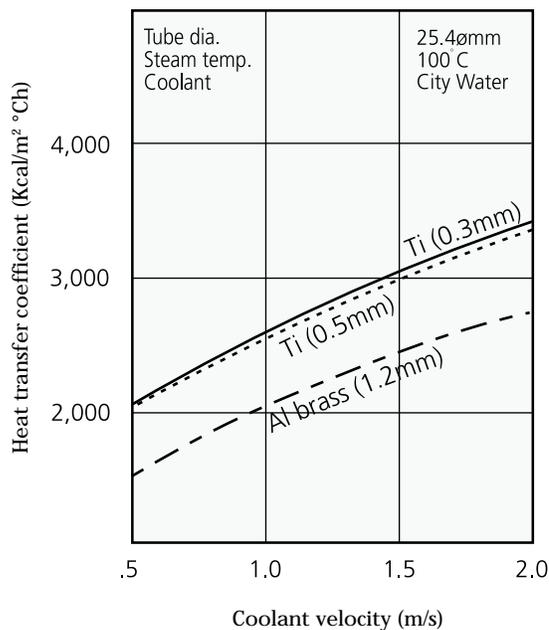
In power plants, refineries, air conditioning systems, chemical plants, offshore platforms, surface ships and submarines, titanium's life span and dependability are proven. In fact, with over 300 million feet of welded titanium tubing in power plant condenser service, there have been no reported failures 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 dropwise 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 dropwise 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 has been proven to increase 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 life cycle 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, light weight, 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 firemain 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 H₂S, CO₂, 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 and 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, H₂S, CO₂, 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 as 100 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. In personal armor, titanium's toughness, light weight and low modulus combine to offer protection with less discomfort. Vests generally are comprised of titanium panels backed by other materials, so the role of the titanium and its ballistic requirements can vary.

Metal Recovery and Finishing

Hydrometallurgical extraction of metals 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.

Pulp and Paper

Due to the recycling of waste fluids and the need for greater equipment reliability and life span, 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 Desulfurization

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); superconducting alloys (50%Nb - 50%Ti used in electromagnets and energy storage and transmission); shape memory alloys (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 Ti-Al 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.

Currently, two application areas are the focus of attention. The National Aerospace Plan provides the main impetus for development activity in both airframes and hypersonic engines. The Integrated High Performance Turbine Engine Technology program seeks to double the current thrust-to-weight ratio of turbine engines. Thus, the high mach number aerospace vehicles and propulsion systems designed to usher in the age of hypersonic flight could become a reality with these materials.

Ferro-Titanium

Titanium scrap is recycled to make ferro-titanium, which is mainly used as a steel and stainless steel additive (as a "getter" to tie up oxygen) for aerospace uses.

Other Industrial Applications

These include anodes for cathodic protection (used to prevent corrosion of other metals); electro-chemical processes (such as electroplating 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.



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, costs have become more stable, availability is good 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 cast from titanium can be bigger, affording a larger “sweet spot” to improve distance and accuracy. The Ti-6Al-4V alloy dominates as a golf club material because it is widely manufactured and inexpensive scrap is readily available.

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 snow shoes 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, 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’s and 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. Pacemaker cases and artificial heart valves are being fabricated from titanium, as are dental fixtures (replacement teeth,

crowns, braces, etc.). Durability and light weight have led to its use in wheelchairs. The metal is also widely used to fabricate surgical devices and centrifuges.

Architecture/Construction

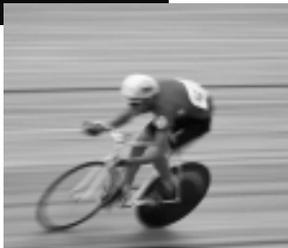
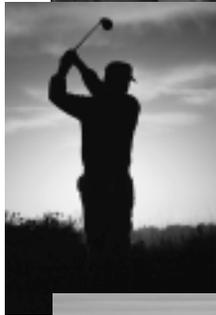
As a building material, titanium outperforms every other architectural metal and is gaining rapid acceptance. Due to its mechanical and physical properties, corrosion resistance and attractive appearance, it is used for exterior cladding, roofs, fascia, canopies and dozens of other building purposes. 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.

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 aftermarkets are also active.



A Historical Perspective

The Early Years: Prior to 1930

Titanium is often perceived as a relatively new, “space age” metal, and perhaps compared to steel, copper and aluminum, it is.

But it was 1790 when Reverend William Gregor, an amateur geologist, discovered titanium in black sand (ilmenite — FeTiO_3) on the Cornish beaches in England. He suggested the new metallic substance be called Manacannite, after a nearby parish.

Five years later, an eminent German chemist, Martin Heinrich Klaproth, recognized a dioxide of the same metal in rutile ore (TiO_2) and called the element “titanium” after the Titans, mythological Greek gods of enormous strength. However, his attempts to isolate the metal failed.

In 1910 an American chemist, M. A. Hunter, finally succeeded in extracting titanium metal from the ore and this marked the birth of the titanium industry. His process involved mixing TiO_2 with coke and chlorine and applying heat, to yield titanium tetrachloride (TiCl_4), which he then reduced with sodium. The Hunter Process yielded very high purity metal which was ductile when hot, but brittle when cold; it was mainly used as an alloying element in steel. Titanium dioxide was also a by-product of Hunter’s Process and it was recognized as having properties which make it an excellent white pigment. By 1912, TiO_2 began to replace lead oxide in paint.

Because Hunter’s Process generated such high quality titanium, it formed the basis for three commercial sodium reduction plants that operated between the 1950’s and 1992. The high purity of Hunter Process titanium contributed greatly to the acceptance of the metal, notably in the titanium metal powder industry. However, the process proved difficult to scale up.

The Kroll Era: The 1930s - 1949

In the 1930’s, Dr. Wilhelm Kroll invented the first viable, large-scale industrial method for reducing titanium — a production process that bears his name. Rather than using sodium as a reducing agent, the Kroll process uses magnesium, and while the process can yield large amounts of the metal, it leaves a chloride residue and does not recover unreacted magnesium. The emergence of vacuum distillation to remove that contamination and improve process economics overcame the last significant barrier to producing mass quantities of commercially pure titanium. Today, the Kroll process with vacuum distillation is the most widely used method of winning the metal from the ore.

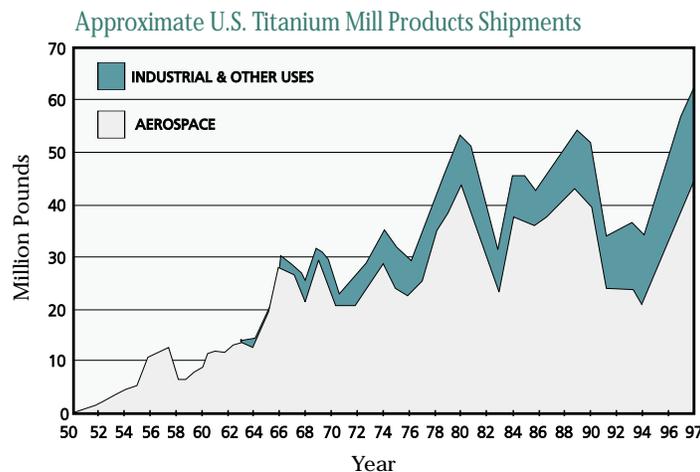
With its exceptional strength-to-weight ratio, corrosion resistance, and temperature attributes, as well as a practical means of production, titanium attracted US Department of Defense attention in 1946 as the best answer to design problems in high performance aircraft. The modern-day titanium industry was truly launched in the late 1940’s, when it was first used in flight — on the Douglas Aircraft X3 Stiletto.

The Aerospace Years: 1950 - 1980

For many years titanium remained almost exclusively a jet engine and airframe material. Each new aircraft used a greater percentage of titanium and by 1957, U.S. mill product shipments reached 12 million pounds, 96% of which was devoted to aerospace use.

During the 1960’s, commercial airline fleet buildup and corresponding technical advances in titanium production, alloys and quality caused use of the metal to surge. Throughout the next two

decades, despite the aerospace industry’s historically cyclical nature, the overall trend was a rise in the use of the metal in aerospace applications. In 1960, U.S. mill product shipments were 10 million pounds; by 1970, that figure tripled, to 30 million pounds, and in 1980 it was over 50 million pounds.



Source: ITA

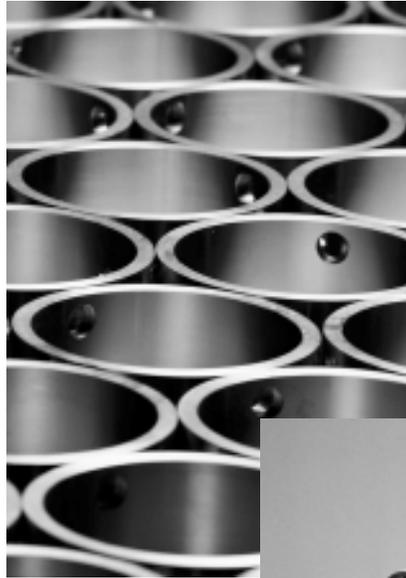
The Diversification Years: 1970 - 1995

Since the late 1950's, it was recognized that titanium's natural corrosion resistance made it a strong candidate for industrial uses. In 1959, titanium tubing was installed in power plant heat exchangers cooled with seawater and, over the next several years, it showed absolutely no signs of pitting or corrosion.

Building on that success, titanium manufacturers actively pursued industrial applications. In 1971, the first power plant to use titanium tubed surface condensers went on-line and, by 1975, this was the fastest growing industrial application for titanium.

Titanium producers have also successfully introduced the metal and its alloys into a variety of industrial and other uses. The chemical processing industry uses it for heat exchangers, process flow equipment and vessels, primarily for its corrosion resistance and resultant low life cycle cost. For the oil and gas industry, it is crucial in offshore exploration and production and subsequent hydrocarbon processing. It is used in consumer products from eyeglass frames to jewelry; as an architectural and racing car material and in common recreational products from golf clubs to bicycles. Titanium improves the quality of individual lives when it is used for medical implants, prosthetic devices, eyeglasses and even lightweight wheelchairs.

By 1997 U.S. mill product shipments were over 60 million pounds, of which 40% was used in applications other than aerospace.



The Present

The reasons for titanium's growth over the past 40 years — in both aerospace and industrial/commercial applications — are numerous.

Of course, the metal remains a staple of the aircraft industry. With each new design, aircraft manufacturers make planes larger and also increase the amount of titanium used in each plane. Titanium usage on Boeing aircraft has increased from 2% empty weight on the 737 to 8% on the 777.

Abundant raw material supply and investments to improve manufacturing technology and increase capacity have increased the metal's availability and lowered its cost. Research and development have yielded an ever-broadening range of alloys and



product forms suited to specific needs. Educational efforts have promoted the ease of common fabrication techniques, such as machining, forging and Tungsten Inert Gas welding.

With these developments, the titanium industry foresees promise for the metal's expanded role in automotive uses, sour and offshore hydrocarbon production, chemical and petrochemical processing, marine applications, water desalination and architecture.

From Black Sand to a Range of Mill Products

Extracting titanium from the ore

Titanium is the fourth most abundant metallic element in the earth's crust. In its elemental form it occurs primarily as ilmenite (titanium-iron oxide — TiFeO_3) and rutile (titanium dioxide — TiO_2). Although these compounds are found on all seven continents, Australia is by far the largest supplier of both. Common black beach sand is rich in rutile, which has the highest titanium content of any source material. About 95% of all titanium mined is used to manufacture TiO_2 , an important pigment that adds whiteness, brightness and opacity to paint, plastic, paper and ink. The other 5% is used to manufacture metal.

To produce pure titanium, the ore — usually rutile — is converted to titanium metal “sponge” (so-called for its ocean-sponge-like appearance) in two distinct steps. First the TiO_2 is mixed with coke or tar and charged in a chlorinator, where chlorine gas is passed through the heated, fluidized bed charge. The titanium ore reacts with the chlorine to form titanium tetrachloride (TiCl_4), a colorless liquid, and the oxygen is removed as CO and CO_2 .

The TiCl_4 is then reacted in the Kroll process, which uses magnesium as a reducing agent under an inert atmosphere. The resultant metallic sponge is then either leached, inert-gas swept or vacuum distilled to remove the excess magnesium chloride and unreacted magnesium metal, which are recycled. Vacuum distillation results in lower levels of magnesium, hydrogen and chloride. The pure titanium sponge must meet stringent specifications to assure control of the ingot's composition.

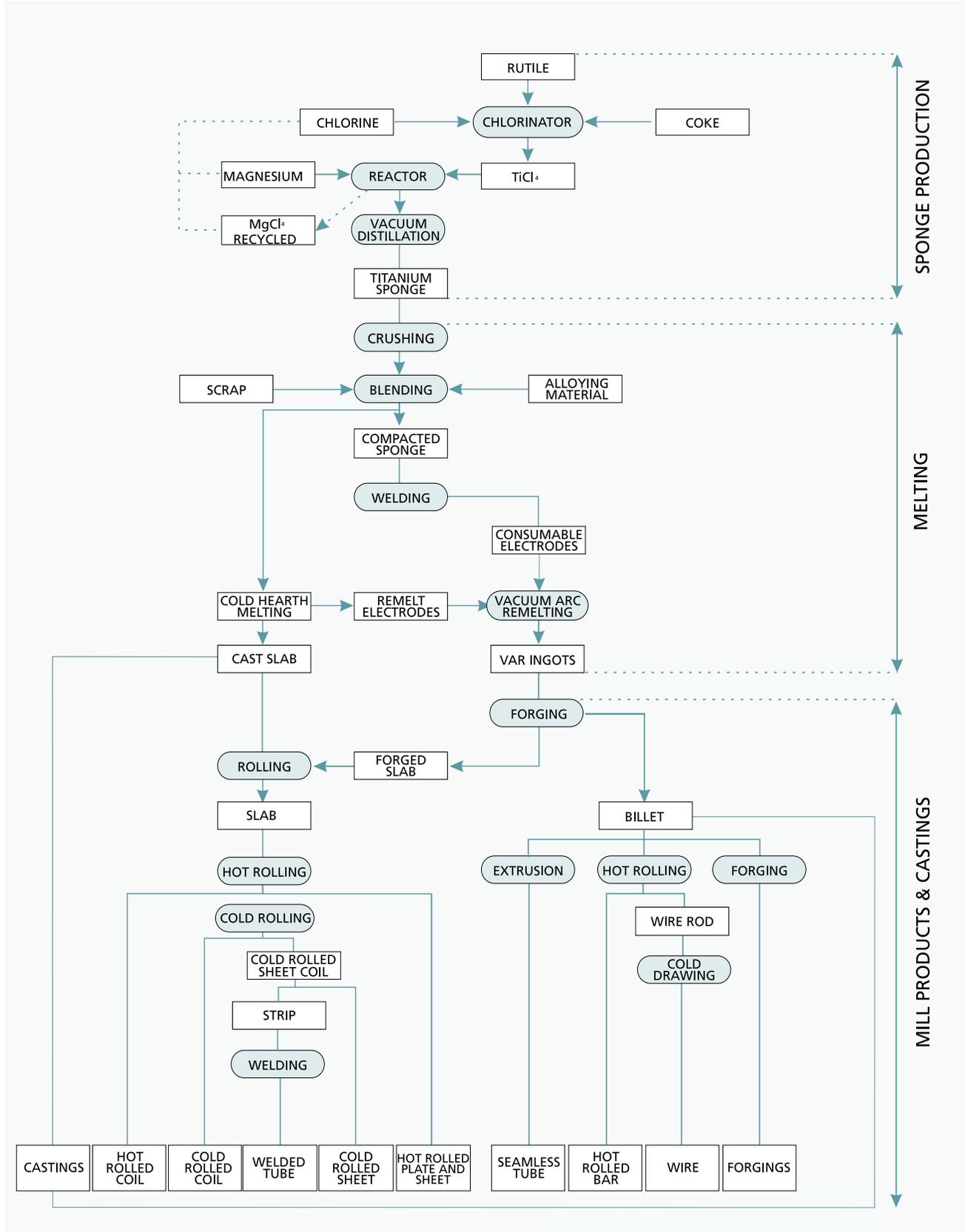
Melting to Ingot: Vacuum Arc Remelting and Cold Hearth Melting

Melting is the next step. This takes place in either a vacuum arc remelt furnace, to produce VAR ingots typically used for aerospace applications, or in a cold hearth (electron beam or plasma arc) furnace, to fulfill industrial requirements, or to produce feedstock for a subsequent VAR melt.

For vacuum arc remelting, the titanium sponge is crushed and blended with the desired alloying elements, such as aluminum, vanadium, molybdenum, tin and zirconium. (The percentage of each alloying element in the final metal is expressed as a number in front of its atomic symbol. For example, Ti-6Al-4V consists of 90% titanium, 6% aluminum and 4% vanadium.) The composition is then pressed into briquets which are welded together to form an electrode. In the VAR furnace, the electrode is “consumable melted” by an arc struck between it and a layer of titanium in a water-cooled copper crucible. The molten titanium on the outer surface solidifies on contact with the cold wall, forming a shell or skull to contain the molten pool. The ingot is not poured, but solidifies under vacuum in the melting furnace. A second melt insures homogeneity of the ingot for industrial purposes; a triple melting operation is used for all metal destined for aerospace use. The resultant VAR ingots are cylindrical shapes weighing up to 30,000 pounds, which are forged to slabs or billets, then formed to mill products.

The alternative sponge melting process uses a cold hearth furnace. Here, the crushed sponge and alloying elements can also be mixed with inexpensive recycled titanium scrap before melting, to reduce costs. The mixture is melted by either electron beams in a vacuum or by plasma arc torches under a positive pressure of helium. The metal flows across the cold hearth, where it forms a pool that allows impurities to sink to the bottom or to be evaporated. Cold hearth melting removes both hard alpha and high density inclusions and is the preferred method for producing clean titanium for aerospace applications. Because it can use a high percentage of scrap, cold hearth melting is also used to produce affordable titanium for industrial and commercial uses. The molten titanium is direct cast into a near net shape, which can be a slab intended for further processing, or a remelt electrode which can then be VAR melted to meet aerospace requirements. Combination cold hearth/VAR melts can eliminate inclusions and defects that even triple VAR melting cannot remove.

Typical Production Flow Chart for Titanium Sponge, Mill Products and Castings



Diverse Mill Products For Multiple Uses

VAR ingots and cold-hearth melted, cast slabs are pressed or rotary forged into slabs (rectangular shapes) or billets (rough round bar or various other shapes). Then, hot forming produces forgings, rollings and extrusions. This can be followed by cold rolling and common processing techniques to create mill products — basic structural shapes with desired properties that maximize metal utilization. The majority of aircraft and some industrial components require hot working to overcome springback, minimize stresses and reduce the high forming forces needed for titanium alloys. Superplastic forming and diffusion bonding under pressure and temperature have recently found acceptance. All mill products are available in the spectrum of alloys and grades.

Forgings

The workhorse of the aerospace industry and a feedstock for additional mill products, forgings are available in a wide range of sizes. New developments in precision forging now provide near-net shapes with improved material efficiencies.

Billet

Billet can have round, square, rectangular, hexagonal or octagonal shapes. Cross-sectional area is equal to or greater than 16 square inches and width is less than five times thickness.

Rod and Bar

Rounds have diameters greater than ½” and less than or equal to 4½”. Squares have cross sections less than 16 square inches. Rectangles have cross-sections less than 16 square inches, thicknesses greater than ⅜” and widths less than or equal to 10 inches.

Plate

Hot-rolling produces plate, which is generally available in thicknesses greater than ⅜” and width greater than 20”. Vacuum creep flattening is widely used to achieve critical plate flatness.

Sheet and Strip

Sheet is flat-roll product that is typically less than ⅜” thick, and produced by either hot or cold rolling. Strip is cut from cold-rolled and annealed sheet.

Pipe and Tube

Pipe and tube can be manufactured as either welded or seamless product in a variety of standard diameters and wall thicknesses. Titanium pipe, fittings and flanges are normally available in standard schedules and sizes.

Extrusions

Titanium is cost-effectively extruded into desired near-net shapes by forcing heated metal through a die. Extrusions maximize material usage and reduce the need for downstream milling, welding or assembly.

Fastener Stock and Wire

This is limited to rounds with diameter less than or equal to ½”.

Other Common Product Forms

These include weld wire, fasteners, screws, nuts, bolts, washers and rod.

Casting: Efficient Production of Near Net Shapes

Casting is the most advanced and diversified of the net shape technologies. It offers greater design freedom and significantly reduces the need for expensive machining or fabrication to attain the desired shape. Commercial casting began in the late 1960’s and today the technology has matured to routinely supply critical gas turbine engine, air frame, chemical process and marine products.

Both precision investment casting as well as rammed graphite (sand) molding systems are employed. The economy of investment casting often favors it as an alternative to fabrications, hog-outs and sheet metal build up assemblies. Investment casting can be used to create large, tolerance-critical parts such as heat shields, fan frames and missile components, as well as smaller parts such as valve bodies. The same pattern equipment used to produce steel parts is often used to produce titanium chemical pump and valve components, while aerospace parts normally require their own tooling.

Mechanical properties of titanium castings are generally comparable to their wrought counterparts. Toughness and crack growth resistance are generally superior, strength is almost the same, while high cycle fatigue is normally a little lower. Hot isostatic pressing (HIPING) is used to eliminate internal porosity in castings, in order to improve fatigue life.

Powder Metallurgy: A Promise of Lower Cost and Wider Uses

Titanium powder technology may offer lower costs in the manufacture of near-net shapes and, with the potential of lower cost powder via plasma quenching production, it could open a wider range of applications.

Conventional Techniques From the Straightforward to the Sophisticated

Conventional metal processing tools and procedures can be used to form, machine and join titanium and its workability is comparable to that of $\frac{3}{4}$ hard stainless steel. The technology of fabricating titanium has also evolved to offer a wide range of highly sophisticated techniques. End application specifications and economics should determine which processes are used.

Although titanium is readily fabricable, some distinct differences from other structural metals should be recognized: lower modulus of elasticity, higher melting point, lower ductility, propensity to gall and sensitivity to contamination in air at temperatures above 800°F (425°C). Also, consideration must be given to the grade or alloy, heat treatment and metallurgical condition.

Forming

Titanium can usually be cold worked on equipment designed for stainless steel or nickel-based alloys. Although it can be readily bent, sheared, pressed, deep-drawn and so on, it is necessary to take into account titanium's strong springback characteristics. Press brakes (used for forming sheet and plate), shears, cold rolls, hydro-press forming, drawing and pilgering equipment can all be used.

Welding

Welding titanium and its alloys is readily performed in the field, without a vacuum, but it is necessary to eliminate reactive gases (including oxygen, nitrogen and air) and to maintain cleanliness. Welding by means of the Tungsten Inert Gas process (TIG) using argon gas shielding is the most common. Plasma, laser, resistance, electron beam, Metal Inert Gas (MIG), and friction welding are widely practiced.

Machining

While titanium presents a unique set of machining circumstances, all of the customary methods can be used and it is no more difficult to machine than Type 316 stainless steel, depending on alloy grade. Titanium's tendency to gall and its low modulus can be counteracted by using consistently sharp tools; heavy, non-stop feeds; rigid set-ups; slow speeds and an abundance of soluble coolant. Work hardening rate is less than that for stainless steels. Drilling and cold saw cutting require sharp, clean tools with good chip removal and ample coolant. Grinding also requires effective use of coolant as well as proper wheel and wheel speed selection.

Cutting

Torchcutting with oxyacetylene flame can be accomplished on titanium sections up to 6" thick. Waterjet and laser cutting are widely practiced.

Cladding

A range of processes is available for cladding, primarily for industrial equipment applications. Explosive bonding and mechanical fastened loose lining have been used for years. More recently roll cladding, resistance weld lining and diffusion bonding are being used.



The Alpha and Beta Forms of Titanium and Its Alloys

Pure titanium exists in two crystallographic forms. The first is alpha, which has a hexagonal close-packed crystal structure that is stable up to 1620°F (880°C). At that point, it transforms to a body-centered cubic structure, the beta phase, which is stable to the melting point.

As alloying elements are added to pure titanium, they tend to change the temperature at which the phase transformation occurs and the amount of each phase present. Alloy additions tend to stabilize either the alpha phase to higher temperatures or the beta phase to lower temperatures. The most important alpha stabilizers are aluminum and oxygen; the key beta stabilizers include molybdenum, vanadium, chromium and iron.

There are four basic classes of titanium-based materials, each favoring selected, specific characteristics. The family of titanium alloys offers a full range of strength properties from the highly-formable, lower strength to the very high-strength. Most of the alpha-beta and beta alloys can provide a myriad of strength-ductility property combinations through adjustments in alloy heat treatment and/or composition. With the wide selection of titanium alloys available, optimum choice for a given environment is almost always possible.

Commercially Pure (Unalloyed) Titanium

CP titanium is less expensive, generally more corrosion resistant and lower in strength than its alloys, and is not heat-treatable. It is highly weldable and formable, and used primarily in applications requiring corrosion resistance and high ductility, where strength is not a prime consideration. Grade 1 is the purest, used in many chemical and marine applications; Grade 2 is considered an industrial 'workhorse'; Grade 3 has higher strength than Grade 2 and is often used in the same applications; Grade 4 is often used in marine applications. There are also grades with a small palladium content that increases resistance to crevice corrosion at high temperatures and low pH.

Alpha and Near-Alpha Alloys

The alpha alloys are non-heat treatable and are generally very weldable. They have low to medium strength, good notch toughness, reasonably good ductility and possess excellent mechanical properties at cryogenic temperatures. The more highly alloyed alpha and near-alpha alloys offer optimum high temperature creep strength and oxidation resistance as well. All-alpha alloys are used in forgings such as gas turbine engine casings and rings. Near-alpha alloys are used for airframe skin and structural components, seamless tubing and moderately high temperature applications such as jet engine compressor blades.

Alpha-Beta Alloys

Most of the alloys now in use fall into the alpha-beta phase, including Ti-6Al-4V which comes as close as possible to being a general purpose titanium alloy. These alloys are heat treatable and most are weldable. Their strength levels are medium to high. Their hot forming qualities are good, but the high temperature creep strength is not as good as most alpha alloys. Alpha-beta alloys are capable of excellent combinations of strength, toughness and corrosion resistance. Typical applications include blades and discs for jet engine turbines and compressors, structural aircraft components and landing gear, chemical process equipment, marine components and surgical implants.

Beta and Near-Beta Alloys

The beta alloys are readily heat treatable to high strengths, generally weldable, and have good creep resistance to intermediate temperatures. Excellent formability can be expected in the solution treated condition. Beta-type alloys also have good combinations of properties in sheet and heavy sections. Typical applications include high strength airframe components, fasteners, springs, pipe and commercial and consumer products.

HEAT TREATING

Heat Treating - Is the process of altering the properties of a metal by subjecting it to a controlled sequence of thermal cycles. The time of retention at a specific temperature and the rate of cooling are as important as the temperature itself. Heat treatment can be performed to improve machinability, increase toughness, improve cold forming characteristics, alter hardness and tensile strength, up and down, and to relieve residual stress as well as improve shearability.

Annealing - Refers to a variety of operations involving heating and slow cooling to remove stresses and alter ductility and toughness. Annealing softens the titanium making it more workable for shearing, forming and machining.

Stress Relieving - Removes residual stresses from within the metal.

Quenching - Rapid cooling from a specific temperature.

Turning, Grinding and Polishing - Produces bars that are characterized by superior surface finish, dimensional precision and straightness.

ROUGH PRODUCT SHAPES

Ingots - Cylindrical in shape with a 1.5 or more length to diameter ratio. A typical production ingot in 34" diameter by 96" long and weighs 14,000 pounds.

Bloom - Semi-finished billet, slab or bar of titanium that has been hammered, forged or rolled from an ingot.

Billet - Piece of semi-finished titanium square or nearly square in section, made by rolling an ingot or bloom.

Slab - Semi-finished titanium block having a rectangular cross-section in which the width is at least twice the thickness. Slab is also a cast product from EB or plasma melting.

TITANIUM SPONGE PRODUCTION

Titanium Ore - The most common ore used in the titanium metals industry is rutile which is a black beach sand containing +95% TiO_2 . The alternate ore is ilmenite, which is only 55 to 60% TiO_2 with the remainder being iron oxides.

Chlorination - Rutile ore (TiO_2) reacts with chlorine gas at elevated temperatures to yield titanium tetrachloride, a colorless liquid.

Chlorination - Titanium Tetrachloride, $TiCl_4$, Tickle - Titanium Tetrachloride is the product of chlorinating titanium dioxide "with Cl in the presence" of carbon to remove the oxygen and produce $TiCl_4$. As used in the metals industry, it is a clear, colorless liquid at room temperature.

Titanium Dioxide - TiO_2 is a pure white material used as pigment in paint. Over 90% of all titanium ores that are mined end up as pigment. TiO_2 is also used in cosmetics such as lipstick.

Reduction - The process of converting $TiCl_4$ to titanium metal using a reducing agent such as magnesium or sodium.

Magnesium Reduction - Titanium tetrachloride combined with molten magnesium metal in a steel reactor under a controlled atmosphere yields titanium metal in sponge form and magnesium chloride ($MgCl_2$) as a by product. The pores in the spongy mass of titanium are filled with Mg or $MgCl_2$. This residual material is removed either by leaching or vacuum distillation.

Vacuum Distillation - For the vacuum distillation process, 366 stainless steel reactor pots are used. After the reduction is completed, the hot reactor pot is transferred to a cold wall vacuum furnace and the residual Mg- $MgCl_2$ is distilled over into a collection vessel for recovery.

Electrolytic Cell - Magnesium chloride ($MgCl_2$) is electrolyzed to recapture chlorine gas and magnesium metal, both of which are recycled through the process.

Sponge - A porous metal product of the chemical reduction of titanium tetrachloride to metal by the Kroll or Hunter process.

Kroll Process - A process for the production of titanium sponge metal where the reducing agent is magnesium.

Hunter Process - The Hunter Process uses sodium as the reducing agent. The sponge produced is purified by a weak acid leach. Between 1990 and 1994 all of the companies using the Hunter Process have gone out of business or shutdown that section of the plant.

Leaching - Titanium sponge passes through a rotary-leaching vessel (made from titanium) where aqua regia and water remove trace magnesium and other impurities.

Leached Sponge - A sponge metal that has been purified by using a weak acid to remove the impurities, such as unreacted reducing agent or by-product salt from the sponge.

Distilled Sponge - A sponge metal that has been purified by vacuum distillation instead of leaching. The impurities are removed from the pores of the sponge by vaporizing rather than digestion in leaching.

Sponge Mass - Is the 18,000-pound cylindrical block of sponge pushed out of the reactor vessel after the completion of reduction and distillation.

Titanium Crystals - A high purity titanium crystal produced by the iodide of electro-refining process. Normally in the 55 to 90 Bhn range.

Coke - The carbon feed material used in chlorination.

Sodium - The agent used to reduce $TiCl_4$ to titanium metal in the Hunter Process.

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