Titanium and Titanium Alloys: Advanced Materials for Engineering Industries

[1]T.R.Vijayaram, [2]M.P.Natarajan [3]M.Ramarao,[4]D.Ananthapadmanaban,
[1,2]Professor, Department of Mechanical Engineering, Bharath Institute of Higher Education and Research,Chennai 600073, Tamil Nadu, India
[3]Associate Professor, Department of Mechanical Engineering, Bharath Institute of Higher Education and Research,Chennai 600073, Tamil Nadu, India
[4]Associate Professor, Department of Mechanical Engineering, SSN College of Engineering, Tamil Nadu, India

Abstract

Titanium is a low density metal that can be strengthened tremendously by alloying and deformation processing technologies. It is nonmagnetic and has good heat transfer properties. Commercially pure titanium is an unalloyed one in which the purity ranges from 99.5% to 99% titanium. The main elements in unalloyed titanium are iron and other additional elements like carbon, oxygen, nitrogen, and hydrogen. Titanium alloys have very high tensile strength and toughness. They are light in weight; possess extraordinary corrosion resistance, and ability to withstand extreme temperatures. Titanium can be produced in a wide variety of product forms. They are formable and readily machinable. Titanium has the ability to passivity and thereby exhibits a high degree of immunity against attack by most mineral acids and chlorides. 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 high performance applications. In this paper, the history, categories, facts, properties, and applications of titanium and titanium alloys are discussed precisely.

Keywords: Titanium, Titanium alloys, properties, applications

Introduction

Even though titanium is in abundance in nature, it was not found until the 18th century when it was discovered. This can be explained because titanium does not exist by itself but it is found in conjunction with other elements. It is found in the minerals ilmenite and rutile in quantities that it has proven economically profitable to produce them in large quantities while it is also extracted from minerals such as leucoxene, perovskite, brookite, sphene, and anatase. Automotive industries use titanium alloys in engine components due to its durable properties in these high stress engine environments. Commercially pure titanium has acceptable mechanical properties and has been used for orthopedic and dental implants. Titanium is alloyed with small amounts of aluminium and vanadium, typically 6% and 4% respectively, by weight and this mixture has a solid solubility, which varies dramatically with temperature, allowing it to undergo precipitation strengthening. This heat treatment process carried out after the alloy has been worked into its final shape but before it put to use.

Review on the History of Titanium and Titanium Alloys

William Gregor in England first discovered titanium in an impure form in the year 1791. It was later given the name titanium after the titans, in Greek Mythology, the sons of the sky and earth gods by a German chemist, Martin Kloproth, when he found a dioxide of the titanium metal in rutile, and in many other widely dispersed ores. In 1910, pure titanium was manufactured by M. A. Hunter, an American Chemist. Hunter was able to extract the metal from the ores and developed the process of mixing rutile ore, Titanium oxide with chlorine and coke, then applying extreme heat, producing titanium tetrachloride, which was further reduced with sodium to form titanium. The hunter process successfully produced high quality titanium. Dr Wilhelm Kroll, in 1946, developed the process currently used for producing titanium commercially. The Kroll process reduces titanium tetrachloride with magnesium [1, 2]. This multi-batch, high temperature process proves to be inefficient. It drives the price of titanium to the point where its applications are restricted to the high priced, niche markets. The Armstrong process, developed by International Titanium Powder, LLC is a method of making high purity, and fine titanium powder in a continuous process. This process operates at low temperature, in low pressure, and in small volume equipment [5, 6]. Therefore, capital cost and labor cost is greatly reduced. The product does not require the additional purification needed by sponge produced from the hunter or kroll process. The powder is suitable for various applications such as powder metallurgy, spray forming, and for other near net shape processes. Small diameter, and high purity powder is produced directly now. In several engineering applications, titanium takes over heavier, less serviceable or less cost-effective materials. Designs created with the properties provided by titanium often produce dependable, economic and more durable engineering parts. These titanium components often surpass the performance and service life expectations at a lower cost [3, 4].

General Categories of Titanium Alloys

Titanium alloys are metallic materials, which contain a mixture of titanium and other chemical elements. Such alloys have very high tensile strength and toughness. They are light in weight; possess extraordinary corrosion resistance, and ability to withstand extreme temperatures. Generally, alpha-phase Titanium is stronger and less ductile, but beta phase Titanium is more ductile. Alpha beta-phase Titanium has a mechanical property, which is in between both. Titanium dioxide dissolves in the metal at high temperatures, and its formation is very energetic. Automotive industries use titanium alloys in engine components due to its durable properties in these high stress engine environments. Commercially pure titanium has acceptable mechanical properties and been used for orthopedic and dental implants. Titanium is alloyed with small amounts of aluminium and vanadium, typically 6% and 4% respectively, by weight and this mixture has a solid solubility which varies dramatically with temperature, allowing it to undergo precipitation strengthening. This heat treatment process is carried out after the alloy has been worked into its final shape but before it is put to use, allowing much easier fabrication of a high-strength product [7, 8].

Important Properties of Titanium and Titanium Alloys

Generally, alpha-phase Titanium is stronger and less ductile, but beta phase Titanium is more ductile. Alpha beta-phase Titanium has a mechanical property, which is in between both. Titanium dioxide dissolves in the metal at high temperatures, and its formation is very energetic. These two factors mean that all titanium except the most carefully purified has a significant amount of dissolved oxygen, and so may be considered a Ti-O alloy. Oxide precipitates offer some strength, but are not very responsive to heat treatment and can substantially decrease the alloy's toughness. Nitinol, a shape memory alloy, is a mixture of titanium and nickel, while niobium-titanium alloys are used as wires for superconducting magnets. Many alloys also contain titanium as a minor additive, but since alloys are usually categorized according to which element forms the majority of the material, these are not usually considered “titanium alloys" as such. Titanium is a strong, light metal [6, 7]. It is as strong as steel but 45% lighter. It is also twice as strong as aluminium but only 60% heavier. Titanium is a lightweight metal having a density of 4.54 gm/cc, which is intermediate between that of aluminium and iron density. It has a melting point of 1668 degree C, which is higher than that of iron, and a modulus of elasticity of 16800000 lb/square-inch, which is intermediate between the values for aluminium and iron. The crystal structure of titanium is HCP at room temperature. Pure titanium can be cold rolled at room temperature to above 90 % reduction in thickness without serious cracking. Such extensive deformability is unusual for HCP metals like titanium and it is mostly related to the low c/a ratio of titanium. The relatively high ductility of HCP titanium is attributed to the many operative slip systems and available twinning planes in the titanium crystal lattice.

Table 1 General Fact Of Titanium And Titanium Alloys

Lustrous, Silver Metal
Superior Strength, Yet Light Weight
Corrosion Resistant
It can withstand Extreme Temperatures
Capable of being Fabricated into A Variety of Parts
Biocompatible : Medical Implants Used in the Human Body

Plastic deformation in titanium HCP is dominated by twinning planes. The type of slip in titanium is also very dependent on the concentration of interstitial impurity atoms such as oxygen and nitrogen. Most of the titanium alloys are ternary and quaternary and are not binary alloys. Titanium alloys are classified according to the phases present in their microstructure. Alloys that consist mainly of the alpha phase are called alpha titanium alloys, whereas those that contain principally the alpha phase along with small amounts of beta stabilizing elements like aluminium, gallium, and germanium. Alloys that consist of mixtures of alpha and beta phases are classified as alpha-beta alloys. Finally, a titanium alloy in which the beta phase is stabilized at room temperature after cooling from a solution heat treatment classified as beta alloys. Alpha titanium alloys are non-heat treatable and weldable. They have medium strength, good notch toughness, and good creep resistance at elevated temperatures. Alpha-beta titanium alloys are heat treatable to attain a moderate increase in creep strength. They also have good forming properties, but do not have good creep resistance at elevated temperatures as the alpha titanium alloys or nearly alpha titanium alloys. Beta alloys are heat treatable to achieve very high strengths and are readily formable. These alloys have relatively high density and in the high strength condition have low ductility [6, 7, 8]. The facts of titanium and titanium alloys in general, physical, mechanical, thermal properties and applications are presented below in Table-1 and Table-2.

Table 2 Physical, Mechanical And Thermal Properties Of Titanium And Titanium Alloys

Tensile Strength	234 MPa
Yield Strength	138 MPa
Density of Solid	4509 Kg/m3
Molar Volume	10.64 cm3
Velocity of Sound	4140 m/sec
Modulus of Elasticity	115 Gpa
Modulus of Rigidity	44 Gpa
Bulk Modulus	108 Gpa
Poisson's Ratio	0.33
Percentage Elongation	54%
Mineral Hardness	6.0
Brinell Hardness	716
Vickers Hardness	970
Electrical Resistivity	0.0000004 micromtr.
Thermal Conductivity	22 W/m/K
Thermal Expansion	0.00086 / K
Enthalpy of Fusion	18.70 KJ / mol
Enthalpy of Vaporization	425 KJ / mol
Enthalpy of Atomization	471 KJ / mol
Melting Point	1668 Degree C
Boiling Point	3287 Degree C
Super Conduction Temperature	-272 degree C

Identification and Selection of Titanium Alloys for Service

Titanium and its alloys are used primarily in two areas of application where the unique characteristics of these metals justify their selection: corrosion resistant service and strength efficient structures. Corrosion applications normally use lower strength unalloyed titanium mill products fabricated into tanks, heat exchangers, reactor vessels for chemical processing, desalination and power generation plants. In contrast, high performance applications such as gas turbines, aircraft structures, drilling equipment, submersibles, biomedical implants, and bicycle frames. 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 or reliability requirements. Alloys for high performance applications in strength efficient structures are normally processed to more stringent and costly requirements than unalloyed titanium for corrosion service [6, 8]. For lightly loaded structures, where titanium normally is selected because it offers greater resistance to the effects of temperature than aluminium. Commercially pure titanium satisfies the basic requirements for corrosion service. Due to its unique corrosion behavior, titanium is used extensively in prosthetic devices such as heart valve parts, load bearing hip and other bone replacements. Titanium and titanium alloy castings are used in surveillance and guidance systems for aircraft and missiles to support the optics where wide temperature variations are encountered in service.

Application of Titanium and Titanium Alloys

Pure titanium is considered as an alpha phase alloy in which the oxygen content determines the grade and strength. It is lower in strength but more corrosion-resistant and less expensive than titanium alloys. It is used primarily when strength is not the main requirement. It has an excellent to many chemical environments. It is finding increasing use in the petroleum processing industry, especially for heat exchangers. It is used in refineries, since it is resistant to sulphides, chlorides, and many other chemicals encountered in petroleum refining. The addition of 0.2% palladium to commercially pure titanium improves its corrosion resistance in reducing media. Unalloyed titanium are used to design and process air frames, desalination equipments, marine chemical parts, plate type heat exchangers, cold spun or pressed parts, platinised anodes, aircraft engines, condenser and evaporator tubes, surgical implants, high speed fans, and gas compressors [1,2.8].

One important and commercial alpha titanium alloy, which we use today ha the nominal composition of Ti-5Al-2.5Sn.It is an all-alpha alloy because aluminium and tin both stabilize the alpha phase in titanium. This alloy is weldable and has good stability and oxidation resistance at elevated temperatures, and its strength is moderate. All alpha titanium alloys have the HCP crystal structure of titanium. Alpha titanium alloy is a weldable alloy for forgings and sheet metal parts such as aircraft engine compressor blades and ducting, and used to produce steam turbine blades. Besides, it is applied as a special grade material for high-pressure cryogenic vessels operating down to -423 degree F. Hence, for applications requiring good ductility at low temperatures, a low oxygen type Ti-5Al-2.5Sn alloy is produced. It has desirable properties such as good weldability, good creep resistance, and toughness, high strength, low ductility, and high modulus. This alloy is normally used in the annealed condition, after performing mill annealing and duplex annealing. Near alpha titanium alloys are applied to produce airframe and jet engine parts requiring high strength up to 455 degree C, parts and cases for jet engine compressors, airframe skin components, and jet engine parts. Ti-6Al-4V is the most important and widely used titanium alloy, accounting for 60% of the titanium market in 1989. It can be readily welded, forged, and machined, and it is available in a wide variety of mill product forms such as sheets, extrusions, wire, and rod. It is also used extensively for ordnance forgings. For special applications, requiring strengths at elevated temperatures, such as components for advanced jet engines, the Ti- 6Al-2Sn-4Zr-6Mo and Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si alloys have been developed. They are more hardenable and cab be used in heavier sections and as well as at higher temperatures [3, 9].

Alpha-beta titanium alloys are used to manufacture rocket motor cases, blades, and disks for aircraft turbines and compressors, structural forgings and fasteners, pressure vessels, gas, and chemical pumps, cryogenic parts, ordnance equipments, marine components, steam turbine blades, structural aircraft parts, and landing gears, airframes and jet engines, missile forgings, aircraft sheet components, aircraft hydraulic tubing, foils, and components for advanced jet engines. If sufficient amounts of beta stabilizing alloying elements are added to titanium, a structure consisting of all metastable beta phase can be obtained at room temperature by quenching or even in some cases by air cooling. These alloys are usually used in the solution treated and aged condition in order to obtain their high strengths and they have the highest strengths of all titanium alloys, reaching up to 210 ksi. More than 100 titanium alloys have been offered commercially since the titanium industry first formed. Titanium and titanium alloys are used in airplanes, missiles and rockets where strength, low weight and resistance to high temperatures are important. Since titanium does not react within the human body, it is used to create artificial hips, pins for setting bones and for other biological implants. Unfortunately, the high cost of titanium has limited its widespread use. Titanium and its alloys are attractive engineering materials for structural applications in the aerospace industries. They have a high strength to weight ratio, high-elevated temperature properties up to 550 degree centigrade, and excellent corrosion resistance, particularly in most natural environments [1, 9].

These alloys are more expensive than the common metals. These alloys do compete effectively in many areas, where their special properties can be used to advantage. For example, high strength to weight ratio and high elevated temperature properties of titanium alloys are of prime importance in the aerospace industry. The new Beta-21S titanium alloy has the nominal composition as Ti- 15Mo-2.7Nb-3Al-0.2Si and has excellent oxidation resistance and elevated tensile properties for a

metastable beta alloy. In addition, Beta-21S has excellent corrosion and hydrogen resistance. Proposed use of this alloy is for applications involving extended exposure at elevated temperatures. The high molybdenum content of this alloy provides excellent high temperature stability and the niobium content is responsible for its excellent oxidation resistance. Beta-21S has superior oxidat ion resistance compared to commercially pure titanium and has roughly 20 times better oxidation resistance than the Ti-15-3 alloy (Ti-15V-3Cr-3Sn-3Al) after exposure at 650 degree C for 24 hours. Titanium has been one of the key materials used in all space launchers, spacecrafts, and the space station [7]. Table- 3 shown below provides a list of some titanium applications.

TABLE 3 APPLICATIONS OF TITANIUM ALLOYS IN ENGINEERING INDUSTRIES

Name of the Engineering Industry	Application
Aerospace Industry	Gas Turbine Engines, Aircraft Structures, Spacecraft, & Helicopter Rotors
Power Generation Industry	Gas Turbines, Steam Turbines, Piping Systems, Heat Exchangers, & Flue Gas Desulphurization Systems
Chemical Processing Industry	Pressure & Reaction Vessels, Heat Exchangers, Pipe & Fittings, Liners, Tubing, Pumps, Condensers, Valves, Ducts, Filters, & Agitators
Automotive Industry	Automotive Body Panels, Engine Connecting Rods, Valves & Valve Springs, & Rocker Arms
Marine Industry	Surface Ship Hulls, Deep Sea Submersibles, Pleasure Boat omponents, Racing Yacht Components, Shipboard Cooling Systems, Ship Propellers, Service Water Systems, Ducting, Fire Pumps, & Water Jet Propulsion Systems
Oil, Gas & Petroleum Processing Industry	Tubing and Pipe, Liners, Springs, Valves, and Risers
Biomedical Industry	Artificial Joint Prostheses, Bone Plates, Intramedullary Rods, Heart Valves, Pace Makers, Dental Implants, Attachment Wire, Surgical Instruments, & Wheel Chairs
Architectural Industry	Roofing, Window Frames, Eaves & Gables, Railings, & Ventilators
Sports Industry	Bicycle Frames, Gears, Lacrosse Sticks, Racing Wheel Chairs, Horseshoes, Tennis Rackets, Golf Sticks, Scuba Gas Cylinders, Skis, & Pool Cues
Miscellaneous Applications	Shape Memory Alloys, Pollution Control Systems, Hand Tools, Desalination Systems, Military Vehicle Armour, Hunting Knives, & Backpack Cookware

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 segregat ion, high density or low density tramp applications, 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 like oxygen, nitrogen, and carbon are carefully controlled to improve ductility and fracture toughness. Aircraft structural applications, along with high performance automotive and marine applications also require high strength efficiency, which is achieved by judicious alloy selection combined with close control of mill processing [7, 8].

Conclusions

It is concluded that titanium and titanium alloys have very high tensile strength and toughness. They are light in weight; possess extraordinary corrosion resistance, and ability to withstand extreme temperatures. It is stronger and less ductile, but beta phase Titanium is more ductile. Alpha beta- phase Titanium has a mechanical property, which is in between both. Titanium and titanium alloys are used in airplanes, missiles and rockets where strength, low weight and resistance to high temperatures are important. Titanium does not react within the human body. So, it is used to create artificial hips, pins for setting bones and for other biological implants

References

1. Yassin Mustafa Ahmed, Khairul Salleh Mohamed Sahari , Mahadzir. Ishak , Basim Ali Khidhir, Titanium and its Alloy, International Journal of Science and Research (IJSR) ISSN (Online): 2319-7064, Volume 3 Issue 10, pp: 1351-1361, October 2014
2. C. Leyens and M. Peters, "Titanium and Titanium Alloys: Fundamentals and Applications ", Edited by Christoph Leyens, Manfred Peters, Published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, First Edition, 2003.
3. www.RMITitanium.com, "Titanium Alloy Guide", RMI Titanium Company, an RTI International Metals, Inc. Company, Jan, 2000.

4. www.ASM.org, “Titanium and Titanium Alloys”, ASM International web. , Materials News Departments, 2013.
5. Sandvik Materials Technology, “Titanium Alloy”, Sandvik Coromant Web: www.smt.sandvik.com, SE-811 81 Sandviken, Sweden2013.
6. C.Veiga, J.P. Davim and A.J.R. Loureiro, Properties and applications of titanium alloys: A brief review, Properties and applications of titanium alloys: a brief review, Rev.Adv. Mater. Sci. 32 (2012) pp: 14-34, 2912.
7. R. Shivpuri // Trans. Indian. Inst. Metals 57 (2004) 345.
8. T. R. Rautray, R. Narayanan and K.H. Kim // Progress in Materials Science 56 (2011) 1137