Titanium and Titanium Alloys for the Future Metal Working Industry

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1. INTRODUCTION

Commercially pure titanium in its unalloyed state has a purity ranging from 99% to 99.5% titanium. The main elements in unalloyed titanium are iron and the interstitial elements like carbon, oxygen, nitrogen, and hydrogen. 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.

In this article, the history, categories, facts, properties, and applications of titanium and titanium alloys are discussed precisely. Even though titanium is in abundance in nature, it was not until the 18th century that 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 at quantities where it has proven economically profitable to produce 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 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 put to use.

2. HISTORY

William Gregor in England first discovered titanium in an impure form in the year 1971. 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, ilmenite, 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 [1].

The Kroll process reduces titanium tetrachloride with magnesium. 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. 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 [2]. 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.

3. 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 [3]. 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.

4. FACT SHEETS OF TITANIUM AND TITANIUM ALLOYS

The facts of titanium and titanium alloys in general, physical, mechanical, thermal properties and applications are presented below in Tables 1, 2, and 3 [4].

Table 1: General fact sheet

GENERAL FACTS OF TITANIUM AND TITANIUM ALLOYS
1. Lustrous, silver metal
2. Superior strength, yet light weight
3. Corrosion resistant
4. It can withstand extreme temperatures
5. Capable of being fabricated into a variety of parts
6. Biocompatible: medical implants used in the human body

Table 2: Properties of titanium

PHYSICAL, MECHANICAL AND THERMAL PROPERTIES OF TITANIUM	
Tensile strength	234 MPa
Yield strength	138 MPa
Density of solid	4509 Kg/m^3
Molar volume	10.64 cm^3
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 micrometre
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

Table 3: Applications

APPLICATIONS OF TITANIUM AND TITANIUM ALLOYS
1. Airplanes
2. Nuclear disposal
3. International space station
4. All type of spacecrafts
5. Computers
6. Automobiles
7. Buildings
8. Desalination plants
9. Oil rigs/offshore platforms
10. Vessels

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5. PROPERTIES

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 categorised according to which element forms the majority of the material, these are not usually considered "titanium alloys" as such [5]. Titanium is a strong, light metal. 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. It has a melting point of 1,668 degrees C, which is higher than that of iron, and a modulus of elasticity of 16,800,000 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. 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. If it has an alpha phase along with a beta phase, then it is called as alpha-beta titanium alloy. Finally, if an alpha-beta titanium alloy is stabilised at room temperature after cooling from a solution heat treatment, it will become a beta-titanium alloy. 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. Beta alloys are heat treatable to achieve very high strengths and posses excellent formability. These alloys have relatively high density and in the high strength condition have low ductility [6].

6. APPLICATIONS 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 resistance 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 is used to design and process air frames, desalination equipment, marine chemical parts, plate type heat exchangers, cold spun or pressed parts, platinized anodes, aircraft engines, condenser and evaporator tubes, surgical implants, high speed fans, and gas compressors [7].

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One important and commercial alpha titanium alloy, which we use today has the nominal composition of Ti-5%, Al-2.5% and 2.5 Sn. It is an all-alpha alloy because aluminium and tin both stabilise 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-5%, Al-2.5% Sn 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 of up to 455 degrees C, parts and cases for jet engine compressors, airframe skin components, and jet engine parts [8]. Ti-6% Al-4% V 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-6% Al-2% Sn-4% Zr-6% Mo and Ti-6% Al-2% Sn-2% Zr-2% Mo-2% Cr-0.25% silicon alloys have been developed. They are more hardenable and can be used in heavier sections and as well as at higher temperatures.

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 stabilising 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 developed.

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 industry. They have a high strength to weight ratio, high-elevated temperature properties up to 550 degrees centigrade, and excellent corrosion resistance, particularly in most natural environments. 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-0.2S 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 oxidation 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 degrees C for 24 hours. Titanium has been one of the key materials used in all space launchers, spacecrafts, and the space station.

7. 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 have the 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 and is used to create artificial hips, pins for setting bones and for other biological implants.

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