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Classification, Properties and Applications of titanium and its alloys used in aerospace, automotive, biomedical and marine industry- A Review

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ABSTRACT : *Titanium and its alloys are attractive engineering materials used in aerospace, automotive, biomedical, and marine industry because of their outstanding mechanical properties such as high specific strength and physical properties with excellent corrosion resistance and excellent elevated temperature properties. This paper presents a brief reviewonthe classification of titanium and its alloys associated with their chemical composition, properties and applications of titanium and its alloys used in aerospace, automotive, marine, and biomedical industry.The mechanical and physical properties were highlighted. Aerospace industry has been the major area of application of titanium alloys, but one of the major challenges was the development of alloys with improved strength and higher service temperature. In automotive industry, parts were produced for weight saving, but new alloys are being developed with higher service temperature and wear resistance. Titanium materials are widely used in biomedical devices and components, especially as hard tissue replacements and in cardiac and cardiovascular applications. Proper surface treatment will expand the use of titanium materials in both biomedical, and other industries.*

Keywords: *Titanium alloys, classification, applications, aerospace and automotive industry, chemical composition*

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I. INTRODUCTION

Titanium as an element is known for more than 220 years, and is the fourth most abundant structural metals in the Earth's crust after aluminium, iron and magnesium (Veiga et al, (2012), andDanail, et al, (2016)). It is light and nonferrous metal and one of the most chemically active metals thatcan form thin protective layer (5-6nm) when in contact with the environment and thus makes it corrosion resistance material. Thus, titanium and its alloys do not corrode in the atmosphere, in fresh or sea water, they are resistant to corrosion even in the acids of organic origin. Titanium and its alloys have found acceptance in many areas, more especially in aerospace, automotive, biomedical, military, petrochemical, sports, and marine industries because of its high specific strength, and exceptional corrosion resistance.This also explains their preferential use in aerospace sector, chemical industry, medical engineering, and the leisure sector (Renato et al, (2018), and Leyens and Peters, (2003). According to Yassin et al, (2012), and Zherebtsov, et al, (2009) designs created with the properties provided by titanium often produce dependable, economic and more durable systems and components and these titanium components often substantially surpass the performance and service life expectations at a lower overall cost.

Titanium alloys have been developed widely as commercial alloys for over 70 years, fulfilling the requirements for materials with high strength-to-weight ratios at elevated temperatures, initially used in aerospace and defense industries. According to Leyens and Peters (2003), and Danail, et al (2016), that today more than 100 titanium alloys are known, out of which 20 to 30 have reached commercial status. Of these, the classic alloy Ti-6Al-4V covers more than 50% of usage, while 20 to 30% are unalloyed titanium.

The global market for the aircraft industry presents a strong increasing trend as Renato et al (2018), report that recently, the Airbus Company forecast a growing need for new airplanes until 2035, representing an investment of over 5 trillion dollars. In this expanding scenario, several aviation programmes put forth requests for lowering fuel consumption, CO_2 and NO_x emissions during aircraft operation, thus, weight reduction is a key issue for aircraft manufacturers (Uhlmann et al, 2015). Titanium alloys are used in several aircraft components such as landing gears, engine parts, springs, flap tracks, tubes for pneumatic systems and fuselage parts (He et al, (2010) and Danail et al, (2016)). This widespread applicability drives from an impressive set of favorableattributes such as high strength-to-weight ratio, high oxidation resistance, fracture toughness, corrosion resistance, fatigue strength and creep resistance (Yao et al, (2016) and Carvalho, et al, (2016)).

Despite the usefulness of titanium and its alloys, there are limited available articles that addressed the subject in details. Therefore, the aim of this article is to perform a review on titanium alloys with the core subject classification, properties and applications.

II. CLASSIFICATION OF TITANIUM ALLOYS

Titanium is normally available in pure and alloys state. Pure titanium is an allotropic element, normally of a hexagonal structure (HCP) (alpha-α) but transforms to a body centred cubic (BCC) (beta-β) when heated above 882^0C. The addition of alloying elements to titanium influences this transformation temperature and in many alloys results in beta being retained at room temperature, thus producing a material containing both alpha and beta phases or even one which is wholly beta. Also, adding alloying elements to titanium changes the transus temperature. The effect of some alloying elements on the transus temperature is shown in Figure 1. The relative amount of alpha and beta phases in any particular alloy have a significant effect on the properties of that material in terms of tensile strength, hardness, creep properties, ductility, weldability and ease of formability. Characteristics such as creep resistance, weldability, elastic modulus, and toughness are affected by the microstructural features of each class (Renato et al, 2018).

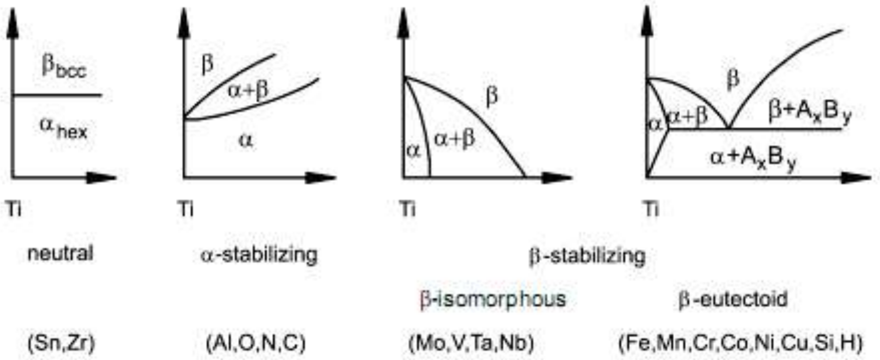

Figure 1 Effects of alloying elements on phase diagrams of titanium alloys (Birhan, 2014)

Depending on their influence on the β-transus temperature, as explained by Leyens and Peters (2001) the alloying elements of titanium are classified as neutral, α-stabilizers or β-stabilizers (Fig. 1).Also,as observed from Fig. 1 there are elements that when added to titanium increase the transus temperature through stabilizing the phase called α-stabilizers (Al, O, N. C), while those that decrease the transus temperature through stabilizing the phase called β-stabilizers (Nb, Ta,V, Mo, Cu, CO, Cr, Ni).Sn and Zr are considered as neutral elements since have no influence on the α/β phase boundary. But as far as strength is concerned, they are not neutral since they strengthen the α phase.Among the α-stabilizers, aluminium is by far the most important alloying elements. The interstitial elements oxygen, nitrogen and carbon also belong to this category. In addition to extending the α phase to higher temperatures, the α-stabilizers develop a two-phase α+β fields. α-stabilizing elements are subdivided into β-isomorphous and β-eutectic elements. Of these, β-isomorphous elements e.g. V, Mo and Ta are more important due to their higher solubility in titanium (Leyens and Peters, 2001).

It is common practice in the metallurgical industry to refer titanium alloys by their structure, hence, alpha-α, alpha-beta (α + β), and beta (β) alloys. As explained by Yassin et al, (2012) and Veiga et al, (2012), these alloys are normally divided into three classes of alloys, designated as: i) alpha (α), ii) alpha-beta (α + β) and iii) beta (β). Table 1 shows how titanium alloys were classified by metallurgical structure with examples. However, Leyens and Peters, (2001) explained that titanium alloys are divided into α, α+β, and β alloys, with further subdivision into near-α and metastable β alloys. This is schematically outlined in a three-dimensional phase diagram, which is composed of two-phase diagrams with an α and β stabilizing elements respectively as observed in Figure 2. According to this scheme, the αalloys comprise commercially pure (CP) titanium and alloys exclusively alloyed with α-stabilizing and/or neutral elements. With addition of minor fractions of β-stabilizing elements, they referred to as near-α. The α + β alloys, the most widely used alloy group, follow this class. At room temperature these alloys have a β volume fraction ranging from 5 to 40%. But if the proportion of β-stabilizing elements is further increased to a level where β no longer transforms to martensite upon fast cooling, the alloys are still in the two-phase field and the class of metastable β alloy is reached. The single-phase β alloys mark the end of the alloying scale of the conventional titanium alloys (Leyens and Peters, 2001).

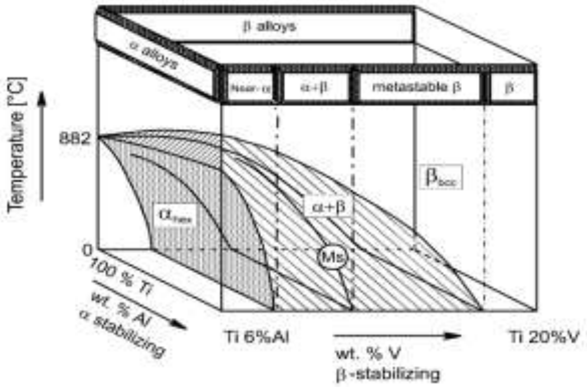

Figure 2. Schematic three-dimensional phase diagram for classification of titanium (Birhan, 2014)

Table 1. Titanium alloys classified by metallurgical structure with examples

Alloy	**Example**
Alpha (α) alloys	Commercially pure Ti -ASTM grades 1, 2, 3, and 4 Ti/Pd alloys – ASTM grades 7 and 11
Alpha (α) + compound	Ti-2.5%Cu – IMI 230
Near Alpha alloys	Ti-8%Al-1%Mo-1%V Ti-6%Al-5%Zr-0.5%Mo-0.2%Si – IMI 685 Ti-6%Al-2%Sn-4%Zr-2%Mo-0.08%Si Ti-5.5%Al-3.5%Sn-3%Zr-1%Nb-0.3%Mo-0.3%Si – IMI 829 Ti-5.8%Al-4%Sn-3.5%Zr-0.7%Nb-0.5%Mo-0.3%Si – IMI 834 Ti-6%Al-3%Sn-4%Zr-0.5%Mo-0.5%Si – Ti 1100
Alpha-Beta (α – β) alloys	Ti-6%Al-4%V Ti-4%Al-4%Mo-2%Sn-0.5%Si Ti-4%Al-4%Mo-4%Sn-0.5%Si – IMI 551 Ti-6%Al-6%V-2%Sn Ti-6%Al-2%Sn-4%Zr-%Mo
Metastable Beta (β) alloys	Ti-3%Al-8%V-6%Cr-4%Zr-4%Mo – Beta C Ti-15%Mo-3%Nb-3%Al-0.2%Si – Timetal 21 S Ti-15%V-3%Cr-3%Sn-3%Al

Different authors like Leyen and Peters (2003), Donachie (2003), Boyer (1996, 2007,2010), and Vinicius and Henriques (2009)have assessed the properties and applications of different titanium alloys used for aerospace applications.

III. PROPERTIES OF TITANIUM AND ITS ALLOYS

The properties of titanium alloys are essentially determined by the arrangement, volume fraction, and individual properties of the two phases α and β. Compared with the BCC β, the hexagonal α is more densely packed and has an anisotropic crystal structure. In comparison with β, α is characterized by the flowing properties:

1. Higher resistance to plastic deformation
2. Reduced ductility
3. Anisotropic mechanical and physical properties
4. Higher creep resistance

Table 2 outlined the essential differences on the basis of physical, mechanical and technological between the three alloys classes – α, α + β and β.

Table 2. Properties of α, α + β and β Ti alloys

Property	A	α + β	B
Density	+	+	-
Strength	-	+	++
Ductility	- /+	+	+/-
Fracture toughness	+	-/+	+/-
Creep strength	+	+/-	-
Corrosion behavior	++	+	+/-
Oxidation behavior	++	+/-	-
Weldability	+	+/-	-
Cold formability	- -	-	-/+

The properties of titanium alloys are essentially determined by two factors as explained by Leyens and Peters, (2003) that is, the chemical composition and the microstructure. Titanium is a highly reactive metal and forms a thin protective film of oxide whenever it is exposed to air or other environments containing available oxygen. This film gives titanium its excellent corrosion resistance.

An increasing scarcity and their growing expense demand reduction in energy consumption for passenger and goods transportation. Titanium and its alloys exhibit a unique combination of mechanical and physical properties and corrosion resistance which have made them desirable for critical, demanding aerospace, industrial, chemical, biomedical, and energy industry service (Annamarie, 2009). The mechanical properties of technically pure titanium are characterized by good combination of strength and ductility. As an example, pure titanium has tensile strength to 540 MPa, yield strength to 410 MPa and elongation ≥ 20%, and in this respect, it is not inferior to the number of carbon and Cr-Ni stainless steels (Danail, et al, 2016). However, these characteristics are dependent on the impurities, especially those by the introduction of oxygen, hydrogen, carbon, nitrogen and to a lesser extent than those by substitution iron and silicon (Masahiko and Takahiro, (1995), ASM, (2002).Table 3list currently used titanium alloys and their most important mechanical properties, while Table 4 shows a comparative analysis of selected physical properties of titanium with some important metals.

The Young’s modulus represents a measure for the stiffness of the material. Its values are directly related to the atomic bonding in the crystal lattice and thus increases with its degree of ordering. Titanium alloys exhibit a low modulus of elasticity which is roughly half that of steels and nickel alloys. This increased elasticity (flexibility) means reduced bending and cyclic stresses in deflection-controlled applications, making it ideal for springs, bellows, body implants, dental fixtures, dynamic offshore risers, drill pipe and sports equipment.

Table 3. Properties of Currently used Titanium and its Alloys

Group	Chemical composition (weight %)	Tensile strength (MPa)	Yield strength (MPa)	Hardness (HV)	Elastic modulus (GPa)	Beta transus temperature T_β (^{0}C)
α alloys						
High purity Ti	99.98 Ti	235	140	100	100-145	882
CP-Ti grade 1	0.2Fe-0.18O	>240	170-310	120	-	890
CP-Ti grade 2	0.3Fe-0.25O					915
CP-Ti grade 3	0.2Fe-0.35O					920
CP-Ti grade 4	0.5Fe-0.40O	>550	480-655	260	100-120	950
Alloy grade 6	Ti-5Al-2.5Sn	861	827	300	109	1040
Near -α						
Ti-6-2-4-2-S	Ti-6Al-Sn4Zr-2Mo-0.1Si	1010	990	340	114	995
TIMETAL 1100	Ti-6Al-2-7Sn-4Zr-0.4Mo-.4Si	1010-1050	900-950	-	112	1010
TIMETAL 685	Ti-6Al-5Zr-0.5Mo-0.25Si	990-1020	850-910	-	120	1020
α + β		900-1200	800-1100	300-400	110-140	995
Ti-6-4	Ti-6Al-4V	1000-1100	950-1050	300-400	110-117	945
Ti-6-6-2	Ti-6Al-6V-2Sn	1100-1200	1000-1100	300-400	114	940
Ti-6-2-4-6	Ti-6Al-2Sn-4Zr-6Mo					
Ti-17	Ti-5Al-2Sn-2Zr-4Mo-4Cr	1100-1250	1050	400	112	890
	Ti-4.5Al-3V-2Mo-2Fe					
Near β	Ti-11.5Mo-6Zr-4.5Sn	960	900	300-500	110	900
SP 700	Ti-3Al-8V-6Cr-4Mo-4Zr	900-1300	800-1200	250-450	83-103	760
Beta III	Ti-10V-2Fe-3Al					
	Ti-15V-3Cr-3Al-3Sn	900-1300	800-1200	300-450	86-115	795

Beta C Ti-10-2-3 Ti-15-3		1000-1400 800-1100	1000-12000 800-1000	300-370 300-450	110 80-100	800 760

α alloys are primarily used in the chemical and process engineering industry. The excellent corrosion behavior and deformability are of prime concern while high strength only ranks second as explained by Annamarie, (2009) and Leyens and Peters, (2003). The four titanium grades 1 to 4 cover a room temperature tensile strength level 240 to 740 PMa. Of these, according to Leyens and Peters, (2003), Grade 1 has the lowest strength level and excellent cold formability, and in deep drawing applications. Grade 2, with tensile strength 390 to 540 MPa, is the most popular cp titanium grade, while higher strength Grade 3 is nearly exclusively used for pressure vessel applications. Grade 4 has the highest strength of up to 740 MPa and is preferentially used for mountings and fittings.

Near-α titanium alloys are the classic high-temperature alloys. This alloy class is ideal for high temperatures since it combines the excellent creep behavior of α alloys with the high strength of α + β alloys. Danail et al, (2016) and Leyens and Peters, (2003), explained that today their operating temperature is limited to about 500 to 550^0C.

Among the α +β titanium alloys, Ti-6Al-4V is by far the most popular titanium alloy. More than 50% of all alloys in use today are of this composition. The alloy was developed in the early 1950s in the USA at the Illinois Institute of Technology and therefore one of the very first titanium alloys to be made. It has good balance properties of its properties and is the most intensively developed and tested titanium alloy, which is a major advantage especially in the aerospace industry, the largest user of Ti-6Al-4V.

Table 4. Comparative analysis of physical properties of titanium and other important metals

Property	Ti	Al	Ni	Fe	Mg	Mo
Density (g/cm^3)	4.5	2.7	8.9	7.9	1.74	10.28
Melting point (^{0}C)	1670	660	1455	1539	650	2623
Elastic modulus (GPa)	115	72	200	215		329
Thermal conductivity (W/Mk)	15-22	221-247	72-92	68-80	154	138
Reactivity with oxygen	High+	High	Low	Low	High+	Low
Corrosion resistance	High+	High	Low	Low	Low	Medium
Metal price	High+	High	High	Low	Medium	Medium
Specific heat (J/kg K)	519	900	440	460	1025	

IV. APPLICATIONS OF TITANIUM AND ITS ALLOYS

The fascination for titanium properties started in the late 1940's and early 1950's, around the Second World War. An increasing scarcity and their growing expense demand reduction in energy consumption for passenger and goods transportation. Here the aerospace, and automotive sectors play a special role with respect to the application of new materials. This is due to its durability, light weight, and excellent corrosion resistance, that make titanium and its alloys are widely used in many industries. It is well known that titanium and its alloys have attractive mechanical and physical properties and high corrosion resistance and these made them one of the best materials used in strategic places like aerospace, military, automotive, biomedical, chemical, and petrochemical industries (Emsley, (2001) and Elias et al, (2008)).Of the primary attributes of these alloys, titanium's elevated strength-to-weight ratio is the primary incentive for selection and design into aerospace engine and airframe structures and components (Annamarie, 2009).An example, Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo are two alloys commonly used for manufacturing components in jet engines, such as fan blades, disks, wheels and sections of the compressor where the maximum temperature is in the range of 300 – 450^0C.Danail et al, (2016), highlighted that titanium and its alloys are used in a wide range of areas as their selection may be based on corrosion resistance or strength, biocompatibility and others. These materials are most widely used in the aerospace, automotive and medicine (Bombac et al, 2007).

4.1 Application of titanium and its alloys in the aerospace industry

An increasing scarcity of resources and their growing expense demand a reduction in energy consumption for passenger and goods transportation. In this case aerospace sector plays a special role with respect to the application of new material. Compared to land-based transportation systems, the much lower system quantities and much higher specific energy consumption aloud designers to tolerate orders of magnitude higher cost for weight savings (Chin, (1981) and (Leyens and Peters, 2001).

Vinicius and Henriques (2009), explained the primary justifications for using titanium in the aerospace industry as earlier narrated by Boyer, (1996).

1. Weight savings (primarily as a steel replacement;
2. Space limitation (replace Al alloys);
3. Operating temperature (Al, Ni, steel alloys replacement);
4. Corrosion resistance (replace Al and low alloy steels);
5. Composite compatibility (replace Al alloys).

According to Danail et al, (2016),and Leyens and Peters, (2003) there are currently over 100 known titanium alloys, but only about 20 to 30 of them find practical application as there is an increasing interest in the use of the category titanium aluminide (TiAl) in the aerospace and automotive industries.

Aerospace has been the major field of application of titanium alloys, especially in the engine and airframe systems where it covers 36% and 7% (Danail, et al (2016), Yang and Liu, 1999).Donachie, (2003), and Danail et al (2016) highlighted that in the US, about 70 to 80% of all orders for titanium alloys are for aerospace industry. The main reasons are the weight loss (mainly as replacement of steel, but also as a replacement of Al); operating temperature (replacement of Al, Ni, alloy steel); corrosion resistance (replacing Al and low-alloy steels (Boyer, (1996), Doerner, (2005), and Boyer et al, (2007). As the strength of titanium alloys are considerably higher than that of Al alloys, the parts can have a smaller cross-section, which directed to weight saving. The substitution of aluminium with titanium alloys can also carried out when the operating temperature exceeds that of aluminium alloys – 130^{0}C (Boyer et al, (2007), Boyer (1996) and Danail et al, (2016). Table 5 listed some application of major titanium alloys used in the aerospace industry.

As pointed out by Boyer et al, (2007), that the Airbus A-380 utilized Ti-10V-2Fe-3Al for landing gear structure similar to that of the Boeing 777. These applications, as with other applications of the alloy are premised on weight reduction in comparison to the high strength steel it replaces as observed in Figure 3. Another advantage of the use of titanium for the landing gear is reduced maintenance costs. The steel landing gear requires costly, tome consuming refurbishment every 7-10 years. Use of titanium eliminates this sustainment requirement.

Table 5. Application of titanium alloys used in the aerospace industry (Danail et al, 2016)

Alloy	Application
Ti-3Al-2.5V (Gr-9)	Used for hydraulichigh-pressure lines, replacing the stainless steel pipe and thus reducing the weight by 40%. It is used for the production of cell structures
Ti-6Al-4V	It is used in gas turbine engines for both static and rotating components, including all parts of the aircraft – fuselage, nacelles, landing gear, wing and tail surface, as well as the structure for the support on the floor.
Ti-5Al-2.5Sn (Gr-6)	Used in tempered state in cryogenic technique because it keeps good strength and ductility in low temperatures. Used in the turbo-pumps high-pressure space shuttles.
Ti-8Al-1Mo-1V	It is used for the blades of military engines (Gas turbine engine components).
Ti-6Al-2Sn-4Zr-2Mo (+Si)	Used mainly in the parts of gas turbine engines, including disks and rotors at temperatures up to about 540^{0}C, in the high-pressure compressors.
Ti-6Al-2Sn-2Zr-2Mo-2Cr +Si	Used for F22 programme for Lockheed/Boeing
Ti-6Al-2Sn-4Zr-6Mo	It is used at temperatures up to about 315^{0}C, primarily for military engines, such as F-100 and F-119, with yield strength of 1035MPa.
Ti-5Al-2Sn-2Zr-4Mo-4Cr	It is used at temperatures below 400^{0}C for fans and compressor disks.
Ti-13V-11Cr-3Al	Widely used in aircraft SR-71 for the wings and body, frames, partitions and ribs
Ti-10V-2Fe-3Al (Timetal 10-2-3)	Almost the whole main landing gear of Boeing 777 is produced from this alloy which leads to a weight saving of about 270 kg per airplane.
Ti-6Al-6V-2Sn	Used for airframe components

Fig. 3. Airbus A-380 landing gear. The labled parts are the Ti-10V-2Fe-3Al components (Boyer et al. (2007).

Landing gear beams on the Boeing 747 and 757 are good examples for illustrating the volume or space limitation problems and their solution by the application of titanium alloys. In fact, according to Boyer (1996), the preferable alloy for this application in terms of cost is aluminium 7075, but the size required to carry the required loads is excessiveand donot fit within the wing envelope. Steel could be used in expense of greater weight. So, the titanium alloys should be better solution.

Veiga et al, (2012), Yassin et al, (2014, and Annamarie (2009), explained that titanium provides enough corrosion resistance so that the painting is not necessary, except in some cases. For example, when the titanium is in contact with aluminium or low alloy steel components paint is needed to prevent galvanic corrosion. The floor support structure under the kitchens and lavatories is submitted to a very corrosive environment which requires the use of titanium to ensure better structural durability. Figure 4 shows examples of titanium alloys applications for the V2500 engine employed by Airbus A320. Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo-0.1Si alloys are most commonly used for the production of A2500 engine (Ikuhiro et al, 2014). According to Boyers et al, (2007), titanium was first produced and used in 1952 for engine gondolas and transport aircraft firewalls in Douglas DC-7. Today, many construction parts of many aircraft are made from titanium alloys.

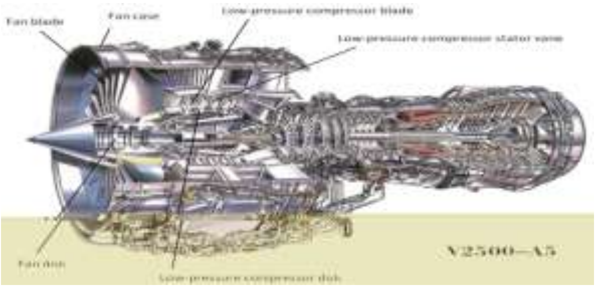

Fig**. 4**. Example of the application of titanium alloy for aero engine (by courtesy of Japanese Aero Engines Corporation)

Titanium is one of the most important materials for example in Boeing 757, supersonic SR-71 Blackbird, jet fighter aircraft F-22 and in space satellites and rockets (Lutjering and Williams, (2007), Leyens and Peters, (2003) and Donachie, (2003)). Titanium and its alloys are commonly used in turbine blades production for aviation engines, various casts and forged parts, shell airframes, firewalls, fan blades, forgings for high strength components for jet engines, gas turbines, rivets, screws, springs, high airframe parts, etc.Table 6 shows some selected aerospace systems and parts versus titanium application. Figure 5. gives a comparative analysis of different materials used in the production of Boeing 747 and 777.

Table 6. Some selected aerospace system and parts versus titanium application.

Materials	Systems and parts
Airframe structures	
Ti-3Al-2.5V	Hydraulic tubing
Ti-15V-3Cr-3Sn-3Al	Springs
Ti-10V-2Fe-3Al; Ti-6-6-2	Landing gear
Ti-6Al-4V	Windows frames
CP-Ti	Floors
Gas turbine engines	
Ti-6Al-4V; Ti-6-2-4-2S	Compressor blades
Ti-6Al-4V; Ti-6-2-4-2S	Compressor disc
Ti-6Al-4V; Ti-6-2-4-2S	Fan discs and blades
Ti-35V-15Cr	Compressor stators
TIMETAL 21S	Nozzle assembly

Annamarie (2009), and Boyer et al (2007), that stemming from the unique combination of high, low modulus and low density, titanium alloys are intrinsically more resistant to shock and explosion damage (e.g. military application) than most other engineering materials.

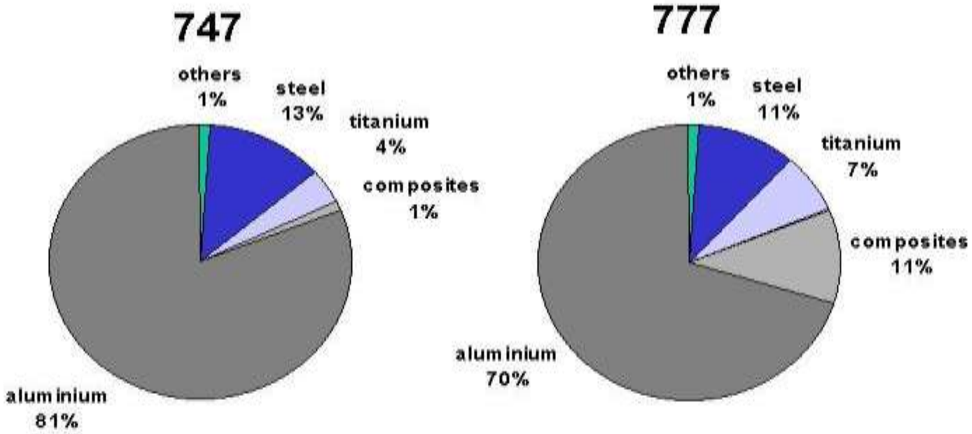

Fig. 5. Comparative analysis of materials used in the production Boeing 747 and 777

Boyer et al, (2007) explained that materials selections and usage are typical of modern fighter's aircraft structures, including polymetric composite materials, 2XXX and 7XXX Al alloy and Ti-6-4 product forms.The materials mix for airframe structural materials selection for modern fighter systems, for F-22 and F-35 are illustrated in Figure 6. This figure demonstrates the importance of the aircraft mission on materials usage; the F-22 with its higher speed and more demanding mission uses more titanium.

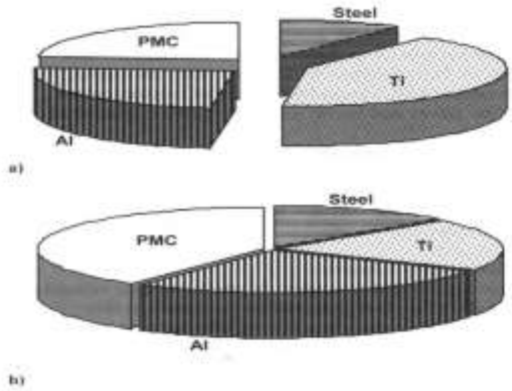

Figure 6. Structural materials mix for the a) F-22 and b) F-35 aircraft

4.2 Application of titanium and its alloys in the automotive industry

The use of new materials in automotive production can lead to both significant weight reductions and oftentimes functional improvements.However, the application of titanium materials in automobile industry as explained by Veiga et al, (2014) and Danail et al, (2016) began with F-1 racing cars in 1980s, being the application carried out primarily in the engine parts. But because of the high cost of titanium alloys, their applications in automobile have been restricted, except for racing and special-purpose cars, despite the strong interest shown in these materials by the industry in terms of lightweight, fuel efficiency, and high performances. In recent years, however, titanium and its alloys have been extensively used for various automobile parts as presented in Table 7.

As observed by Danail et al, (2016) a considerable amount of titanium intake valves, being the majority of them made of Ti-6Al-4V alloy, have been mounted on many cars and motorcycles. But the problems were found and the major among them is the development of surface treatment in order to improve wear resistance and therefore, overcome the low wear resistance of titanium alloys.However, there were several treatments like chromium plating and molybdenum thermal spray coating that proved expensive and are not for prolonged wear resistance.

As observed, Figure 7 provides examples of series of potential applications for titanium components in automotive production while Table 8 lists a number of potential titanium alloys obtained from different literatures.

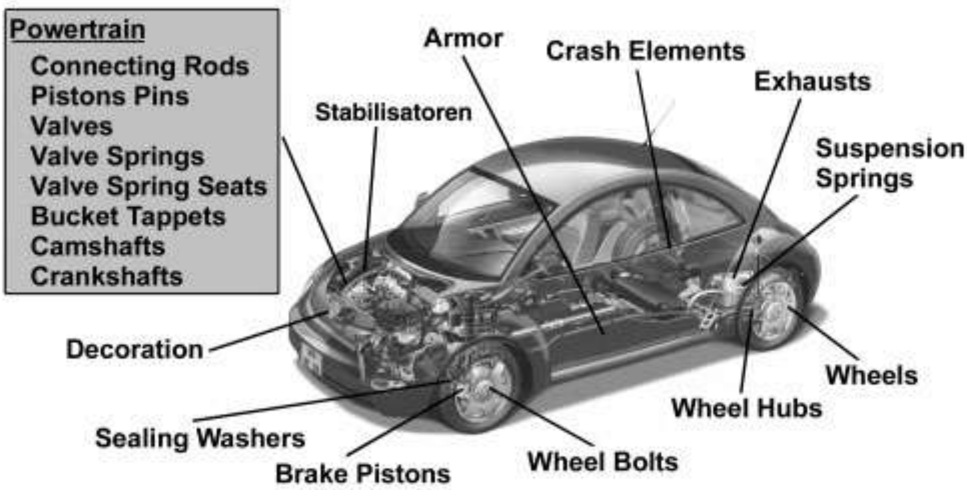

Fig. 7. Examples of possible automotive applications of titanium (Leyen and Peters, (2003)

As observed, the overall scope of application is very small and that given the potential components and automobiles, use ultimately pertains to quite small components and niche applications. Leyens and Peters, (2003 and Veiga et al, (2014) explained that in only very few applications did the use of titanium result from weighing the technical and economic aspects.Figures 8 and 9 are typical examples of components produced using titanium alloys.

Table 7. Application of titanium and its alloys used in automotive industry

Alloy	**Application**
Ti-6Al-4V	Spring suspension, bumper, exhaust valves, connecting rods
Timetal@LCB	Used for suspension spring
Gr-4, Ti-6Al-4V	Body, fuselage
Gr-2, Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo-0.1Si	Exhaust valves
Gr-2	Exhaust system

Table 8. Production of automotive components from titanium alloys (Leyens and Peters, 2003)

Year	**Component**	**Material**	**Manufacturer**	**Model**
1998	Brake guide pins	Grade 2	Mercedes-Benz	S-Class
1998	Sealing washer (brake)	Grade 1s	Volkswagen	All
1998	Gear shift knob	Grade 1	Honda	S2000 Roadstar
1999	Connecting rods	Ti-6Al-4V	Porsche	GT 3
1999	Valves	Ti-6Al-4V & PM-Ti	Toyota	Altezza 6-cyl
1999	Turbocharger rotors	Ti-6Al-4V	Mercedes-Benz	Diesel truck
2000	Suspension springs	LCB	Volkswagen	Lupo FSI
2000	Valve cups	β titanium alloy		
		γ TiAl	Mitsubishi	all 1.81-4 cyl
2000	Turbocharger rotors	Grade 2	Mitsubishi	Lancer
2001	Exhaust system	Ti-6Al-4V & PM-Ti	General Motors	Corvette Z06
2002	Valves		Nissan	Infinity Q 45

Fig. 8. The titanium sport exhaust system weighs as little as2.5 kg (courtesy: REMUS Innovation, Bärnbach, Austria).

Fig. 9. Rear axle spring of the Lupo FSI (left: steel, right titanium alloy Low Cost Beta [LCB])

4.3 Application of titanium and its alloys in the medical industry

It was reported by Xuanyong et al, (2005) that the earlier applications of titanium in medical, surgical, dental devices were based on post World War II advances manufacturing processes as a result of the more stringent requirements demanded by the aerospace and military industry. The increased use of titanium and its alloys as biomedical material stem from their properties, specifically biocompatibility, lower modulus, and better corrosion resistance when compared with more conventional stainless steel and cobalt-based alloys. According to Danail et al, (2016), and Leyens and Peters, (2003), technically pure titanium (Grade 1, 2, 3, 4) and alloy Ti-6Al-4V are the most widely used titanium materials in medicine. These attractive properties were the driving force for the early introduction of α (cpTi) and α + β (Ti-6Al-4V) as well as the more recent development of modern titanium-based alloys and orthopedic metastable β alloys. Xuanyongetal, (2005), further explained that the applications of titanium and its alloys were classified according to their biomedical functionalities.

Hard tissues replacement.

A schematic diagram of a hard tissues in a human body is shown in Figure 10. Hard tissues are often damaged due to accident, aging, and other causes. It is common practice to surgically substitute the damaged hard tissues with artificial replacements. Depending on the regions in which implants are inserted and functions to be provided, the requirements of different endoprosthetic materials are different. Table 9 shows some applications of titanium materials used in medical industry.

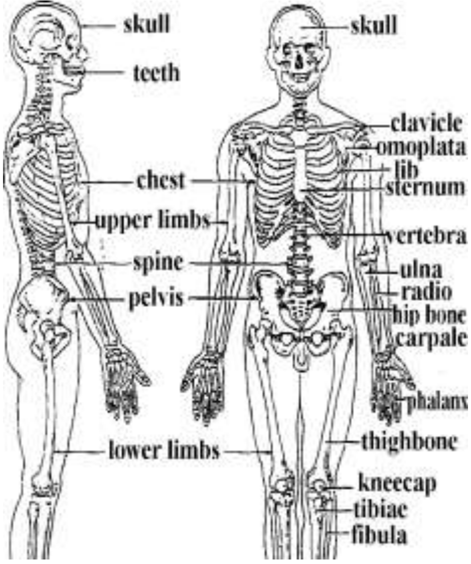

Figure 10. Schematic diagram of hard tissues in human body

As explained by Leyen and Peters, (2003), Xuanyongetal, (2005), titanium and its properties are widely used as hard tissue replacements in artificial bones, joints, and dental implants. As a hard tissue replacement, the low elastic modulus of titanium and its alloys is view as a biomechanical advantage because of the smaller elastic modulus can results in smaller stress shielding. It is a common practice to surgically substitute the damaged hard tissues with artificial replacement.

One of the most common applications of titanium and its alloys is artificial hip joints that consist of articulating bearing (femoral hard and cup) and stem as shown in Fig.11**.**Titanium and titanium alloys are also used in knee joint replacements, which consist of a femoral component, tibial component, patella.

Fig. 11 Schematic diagram of artificial hip joint (left) and knee implant (right) (TitalBestwig Germany)

Table 9. Some applications of titanium and its alloys in medical

Materials	Parts
Joints Ti-6Al-4V	Hip and knee joints
Dental TiMo11Zr6Sn4; Ti-Al-4V CP-Ti (Grades 1, 2, 3 and 4)	
Heart CP-Ti	Valves and connectors

Metals have secured long ago as dental materials with a wide range of applications for functional replacement. Metals have been used as filling materials in preservative dentistry, for fixed prostheses as well as for complete and removable partial dentures and combine dentures with telescopic attachments in dental prosthetics. The spectrum of alloys used in dentistry include gold-platinum, palladium-copper, silver-palladium, nickel-chromium, cobalt-chromium, stainless steel, titanium, and titanium alloys.These days, one of the demands of dentistry is to use only materials with high corrosion resistance and negligible release of ions from toxicological point of view. Therefore, due to its characteristics, the important of titanium and its alloys in dentistry is on the increased continuously. Titanium and titanium alloys are also common in dental implants, which and be classified according to Xuanyong et al, (2005), as subperisteal, transosteal, and endosseous according to their position and shape. The fundamental work for using titanium in dental implantology was performed by Branemark in 1965 (Leyens and Peters, (2003) who inserted the first dental titanium implant. Figure 12 display schematic diagram of the screw shaped artificial tooth. In spite of the large number of alloys in dentistry, there are only a few alloy systems beside titanium that are at same time highly corrosion resistant, biocompatible, and suitable for wide range of applications. Therefore, titanium-based materials are today used throughout dentistry in prosthetics, orthodontics, and implantology.Titanium’s inherent nonreactivity (nontoxic, nonallergenic, and fully biocompatible) with the body and tissue has driven its wide use in body implants, prosthetics devices and jewelry, and in food processing.Stemming from the unique combination of high, low modulus and low density, titanium alloys are intrinsically more resistant to shock and explosion damage (e.g. military application) than most other engineering materials.

Titanium and titanium alloys are common in cardiovascular implants because of their unique properties. As explained by Xuanyong et al, (2005), early application examples were prosthetic heart valves, protective cases in pacemakers, artificial hearts, and circulatory devices. The advantages of titanium in cardiovascular applications are that it is strong, inert, and non-magnetic. It also produces few artifacts under magnetic resonance imaging (MRI), which is a very powerful diagnostic tool. A disadvantage is that it is not sufficiently radio-opaque in fine structures.

Figure 12. Schematic diagram of the screw shaped artificial tooth (Xuanyong et al, (2005)

Besides artificial bones, joints, and dental implants, titanium and its alloys are often used in osteosynthesis, such as bone fracture-fixation. According to Xuanyong et al, (2005), a bone fracture disables the function of the injured limb. Early and full restoration can be achieved by osteosynthesis, a method of treating the bone fracture by surgical means.

4.4. Application of titanium and its alloys in the marine industry

Titanium and its alloys exhibit outstanding corrosion resistance to seawater and aqueous media. It is an attractive material for offshore use, especially in saltwater systems and other hostile environments; but despite its attractive properties it did not find wide application in the offshore industry until in the late 1980s (Leyens and Peters, 2003).However, a major breakthrough occurred in 1986 when Mobil oil company decided to use titanium as a replacement material for corroded and destroyed cement-lined carbon steel piping in the ballast water systems in the North Sea. This installation became a pioneering as it initiated new direction for titanium technological development.

Leyens and Peters (2003) highlighted that in addition to corrosion resistance, high strength- to- weight ratio makes titanium and its alloys attractive to offshore applications since weight is of great concern on both production platforms and vessels. Examples, Njord platform in the North Sea has 110 tons of titanium seawater pipework installed, while Troll platforms have 500 tons of titanium. Table 10 list the candidate grades for offshore environments. As observed, grade 2 (commercial pure titanium) is the most used. It is corrosion resistant, readily formable and ready to weld. This together with relatively low costs and good availability make it the preferred material for topside water management systems. Of the alloys, grade 19 has found the widest applications so far, mostly as high-pressure sampling bottles, downhole tubulars, logging and wireline equipment. Grade 9, 28, 23 and 29 are of current interest for higher riser applications due to their high strength.

Table 10. Titanium alloys for offshore use (Leyens and Peters, (2003))

ASTM grade	UNS Design	Nominal composition	Min. YS (MPa)	Crevice corrosion threshold (^{0}C)	NACE Approved
2	R50400	Unalloyed (CP)	275	80	Yes
16	R52402	Ti-0.05Pd	275	> 250	No
12	R53400	Ti-0.3Mo-0.8Ni	345	> 200	Yes
9	R56320	Ti-3Al-2.5V	485	80	No
28	R56323	Ti-3Al-2.5V-0.1Ru	485	> 250	Yes
23	R56407	Ti-6Al-4V-1O (ELI)	760	80	No
29	R56404	Ti-6Al-4V-1O-0.1Ru	760	> 250	Yes
19	R58640	Ti-3Al-8V-6Cr-4Zr-4Mo	760	> 200	Yes

There are an increasing number of offshore applications for titanium. As explained by Leyens and Peters, (2001), more than forty years ago a few hundred kilograms had been used in chlorination systems and heat exchangers. Presently total consumption is more than four thousand tons. The major applications are seawater and process fluid management systems and heat exchangers. Table 11 shows some selected offshore applications of titanium and its alloys.

Table 11. Selected offshore applications of titanium.

Application	Companies	Projects	Titanium alloy grades
Anchor system pipework	Statoil (Conoco)	Heidrun	2
Booster lines	Statoil (Conoco)	Heidrun	9 (Ti-3Al-2.5V)
Drilling Riser	Statoil (Conoco)	Heidrun	23
Penetration and Manholes	Statoil (Conoco)	Heidrun	2
Taper Stress Joints	Placid Oil	Green Canyon	23 (Ti-6Al-4V ELI
Taper Stress Joints	Ensearch	Garden Banks	23
Taper Stress Joints	Oryx Energy	Neptune	23
Fire Water Systems	Norsk Hydro	Troll B (Oil)	2 (CP)
Fire Water Systems	Elf Petroleum	Brage, Visund, Fry	2
Fire Water Systems	Statoil	Sleipner West, Siri. Norne Sleipner, Veslefrikk	2
Sea Lift Pipes	Statoil	Statfjord A/B, Beryl	2
Ballast Water Systems	Mobil	Hibernia	2
Ballast Water Systems	Mobil	Sleipner West	2
Penetration Sleeves	Statoil	Oseberg	2
Penetration Sleeves	Norsk Hydro	Asgard B	2
Seawater Pipework, fire,	Statoil		2 (500 tons)
ballast and produced water		Jotun	
Pipework	Esso	Njord, Visund	2
Seawater Pipework	Norsk Hydro	Troll A (Gas)	2 (110 tons)
Seawater Pipework	Statoil		2 (500 tons)
Seawater System, Gravity Based System			

V. CONCLUSIONS

This article discussed the review of titanium and its alloys. The major areas addressed were classification, properties, and applications. The data presented in the classification, properties, and applications of titanium and its alloys in aerospace, automotive, medical, and marine industry and inform to make the following conclusions.

1. Titanium and its alloys are considered to be among the promising engineering materials across a range of application sectors. This is due to a unique combination of high strength-to-weight ratio, high corrosion resistance, and melting temperature necessitate interest in the applications of titanium and its alloys.
2. The basis of classification of titanium alloys is according to metallurgical microstructure in annealed state, and on the basis of this, they were divided into four groups: alpha (α) alloys, near alpha alloys, alpha-beta (α-β) alloys, and metastable beta (β) alloys.
3. Titanium and its alloys are used in many areas, like aerospace, military, automotive, medical, marine, petrochemical, sports, each material selected according to use, but the main customers that consumed high percentages of these materials are aerospace, military, automotive industries.
4. Aerospace has been the major area of application of titanium and its alloys, especially in the engine and airframe systems where it comprises 36% and 7% respectively.
5. In those parts that are subjected to high mechanical and/or thermal demands, which include engine components and airframe, high strength and heat resistance alloys are, e.g. Ti-6Al-4V, Ti-13V-11Cr-3Al or Ti-6-2-4-2S, among others are used.
6. The major challenge has been to develop new alloys with improved strength and higher service temperature.
7. The application of titanium and its alloys in automotive industry began with F-I racing cars in the 1980s, in the engine parts, but recently titanium materials are actively used for intake and exhaust valves, connecting rods, suspension springs, gear shift knob, and turbocharger rotor, being the weight saving the major benefits of such applications.
8. The major challenges are the development of new alloys with high service temperature, like for motorcycle exhaust valves application, and new surface treatment to improve wear resistance.
9. The use of titanium and its alloys as biomaterials has been growing because of favorable mechanical properties, e.g. their reduced elastic modulus similar to that of bone, excellent strength to weight ratio, biocompatibility, enhanced corrosion resistance when compared with stainless steel and Co-Cr alloys, processability (casting, welding, deformation, etc.).
10. The use of titanium materials in medical applications includes artificial hip joints, knee joint replacements, dental implant, heart valve and osteosynthesis.
11. The use of titanium alloys was also gaining ground in offshore industry because of the excellent corrosion resistance (like stress corrosion cracking, galvanic corrosion, and corrosion in seawater), high strength to weight ratio.

12. The major applications of titanium materials are in seawater and process fluid management systems and heat exchangers

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