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

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ABSTRACT : *Titanium and its alloys are attractive engineering materials used in automotive 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 review on the classification of titanium and its alloys associated with their chemical composition, properties and applications of titanium and its alloys used in automotive 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.*

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), and Danail, et al, (2016)). It is light and nonferrous metal and one of the most chemically active metals that can 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 favorable attributes 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).

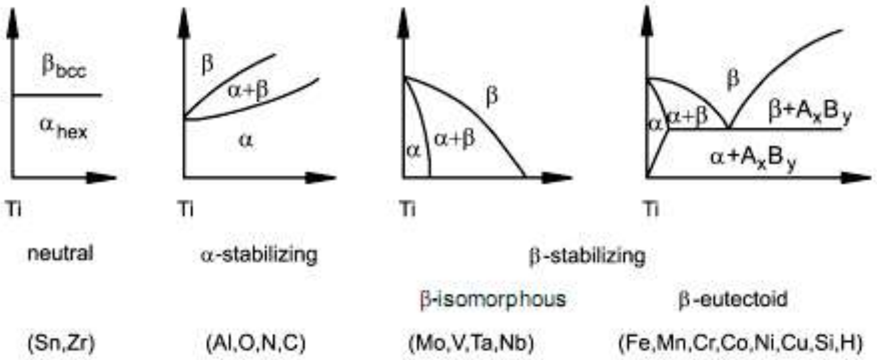

Figure 1 Effects of alloying elements on phase diagrams of titanium alloys (Birhan, 2014)

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 α alloys 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).

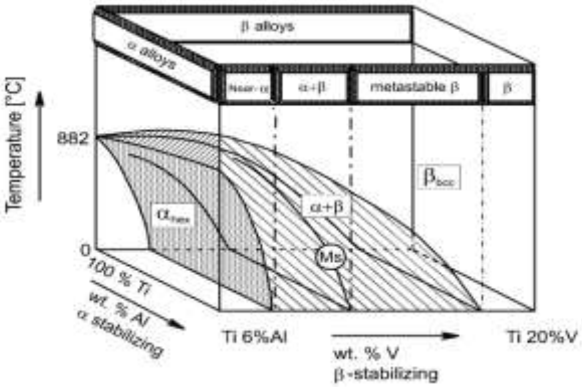

Figure 2. Schematic three-dimensional phase diagram for classification of titanium (Birhan, 2014)

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

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 (RMI Titanium Company, 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 2 gives the mechanical properties of group of selected titanium alloys while Table 3 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 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						
Ti-6-4		900-1200	800-1100	300-400	110-140	995
Ti-6-6-2	Ti-6Al-4V	1000-1100	950-1050	300-400	110-117	945
Ti-6-2-4-6	Ti-6Al-6V-2Sn	1100-1200	1000-1100	300-400	114	940
Ti-17	Ti-6Al-2Sn-4Zr-6Mo					
	Ti-5Al-2Sn-2Zr-4Mo-4Cr	1100-1250	1050	400	112	890
Near β	Ti-4.5Al-3V-2Mo-2Fe					
SP 700	Ti-11.5Mo-6Zr-4.5Sn	960	900	300-500	110	900
Beta III	Ti-3Al-8V-6Cr-4Mo-4Zr	900-1300	800-1200	250-450	83-103	760
	Ti-10V-2Fe-3Al					
Beta C	Ti-15V-3Cr-3Al-3Sn	900-1300	800-1200	300-450	86-115	795
Ti-10-2-3		1000-1400	1000-12000	300-370	110	800
Ti-15-3		800-1100	800-1000	300-450	80-100	760

Table 3. 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 (www.RMITitanium.com.). 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^{0}C. 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 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 Tables 6 and 7 (Leyens and Peters, (2003), Danail et al, (2016), and Veiga et al, (2014).

As observed by Fujii et al, 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 6 provides examples of series of potential applications for titanium components in automotive production while Table 6 lists a number of potential titanium alloys obtained from different literatures.

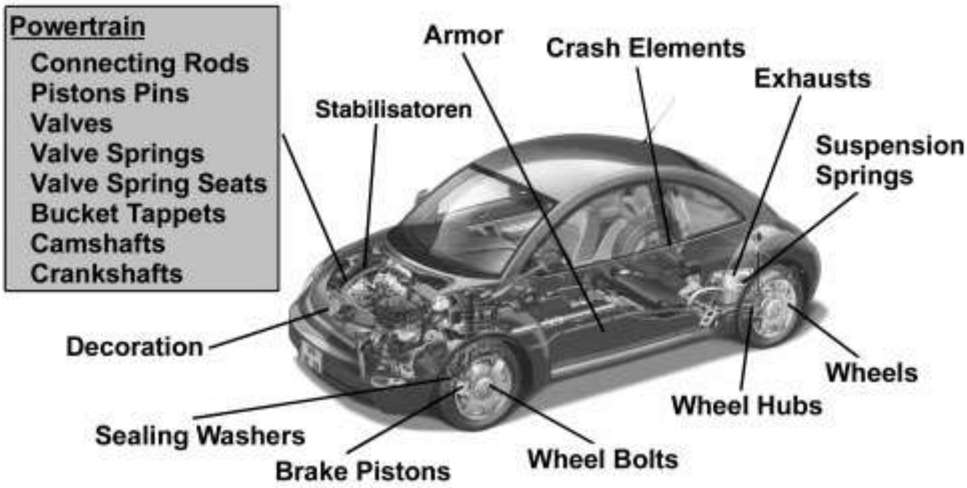

Fig. 6. Examples of possible automotive applications of titanium (Leyen and Peters, (2003)

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 7 and 8 are typical examples of components produced using titanium alloys.

Table 6. 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 7. 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-	General Motors	Corvette Z06
2002	Valves	Ti		
			Nissan	Infinity Q 45

Fig. 7. The titanium sport exhaust system weighs as little as 2.5 kg (courtesy: REMUS Innovation, Bärnbach, Austria).

Fig. 8. Rear axle spring of the Lupo FSI (left: steel, right titanium alloy Low Cost Beta [LCB])

V. CONCLUSION

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 automotive 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. 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.
5. 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.

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