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# Classification, properties and application of titanium and its alloys

Danail Gospodinov, Nikolay Ferdinandov, Stoyan Dimitrov

***Abstract:*** *This paper provides a classification of titanium and titanium alloys associated with their chemical composition and structural state after annealing. Described are their physical, mechanical and technological properties. A short analysis of areas of application of these materials is made.*
***Keywords:*** *Titanium alloys, Properties, Structure.*

## INTRODUCTION

Titanium as a chemical element is known for more than 220 years, and as a concentration in the earth's crust, it is on the fourth place among the metals after aluminum, iron and magnesium. Most authors do refer it to black, refractory metals (its temperature melting is 1668 ° C) [27, 32].

In pure state titanium is rarely used, but in recent years the use of titanium alloys have increased significantly due to the development of methods involved in their production and further processing.

The advantages of titanium and most of its alloys over other well-known structural materials are related to its high mechanical properties in a wide temperature range, low density, excellent corrosion resistance to many aggressive media, low thermal conductivity, non-magnetism, workability in processing and other, which are the qualities that make it a very attractive material.

It and its alloys are used in various fields of industry, aircraft and rocketry, shipbuilding, chemical engineering, food processing, and other industries and medicine [3, 4, 7, 11, 17, 19, 22, 23, 26, 28, 29, 31, 33, 34].

The present work presents the classification of titanium and titanium alloys associated with their chemical composition and structural state after annealing. A review and analysis of their characteristics and properties, as well as the fields of the application of these materials, is made.

## SUMMARY

Titanium is a tightly packed hexagonal lattice (K12), also known as alpha (α) phase, which is stable up to 882 ° C. Above this temperature it undergoes polymorphic conversion to form a beta (β) phase with a volume centered cubic lattice (K8). Titanium belongs to chemically active metals and it is with high corrosion resistance because of a thin layer (5-6nm) $TiO_2$ which forms on its surface limiting direct contact with a metal corrosion protection. Thus, titanium and its alloys do not corrode in the atmosphere, in fresh or sea water, they are resistant to corrosion and cavitation corrosion under tension, and also in the acids of organic origin.

The mechanical properties of technically pure titanium are characterized by a good combination of strength and ductility. For example, technically pure titanium has tensile strength to 540MRa, yield strength to 410MRa and elongation ≥20%, and in this respect it is not inferior to the number of carbon and Cr-Ni stainless steels. These characteristics, however, largely dependent on the content of impurities therein, especially those by the introduction - oxygen, nitrogen, hydrogen, carbon and to a lesser extent than those by substitution - iron and silicon [14]. As they increase strength, they also sharply lower plasticity as gases have the most harmful influence. With hydrogen content above 0,01%, nitrogen over 0,24% or oxygen of more than 0.5% titanium completely loses the ability to process through plastic deformation and brittle breaks, which limits its application. Hydrogen is less soluble in α titanium and leads to the formation of hydride lowering impact strength and the occurrence of hydrogen embrittlement. For this reason, the content of impurities, especially gas is strictly limited.

For the elaboration of different structures alloys of titanium are mainly used. Their main advantages are related to their increased strength, heat and corrosion resistance.

Table 1 presents the names of technically pure titanium and some of its alloys under different standards, and their mechanical properties - tensile strength, yield strength and elongation [8, 16, 20].

Tab. 1 Designation of titanium and its alloys according to different standards

| ASM | ASTM (UNS) | DIN | GOST | BS | UNI 10221 | JIS | Rm, Mpa Rp0,2, Mpa A, % |
|---|---|---|---|---|---|---|---|
| **unalloyed titanium** | | | | | | | |
| Gr -1 | 1 (R50250) | 3.7025 | BT1-00 | 1 | Ti1-Type 1 | Class 1 | 240/170/24 |
| Gr -2 | 2 (R50400) | 3.7035 | BT1-0 | 2,3,4,5 | Ti2-Type 2 | Class 2 | 340/280/20 |
| Gr -3 | 3 (R50500) | 3.7055 | | | Ti3-Type 3 | Class 3 | 450/380/18 |
| Gr -4 | 4 (R50700) | 3.7065 | | 6,7,8,9 | Ti4-Type 4 | Class 4 | 550/480/15 |
| Gr -7 | 7 (R52400) | 3.7235 | | | Ti2Pd-Type7 | Class 13 | 340/280/20 |
| Gr -11 | (R52250) | 3.7225 | | | Ti1Pd-Type11 | Class 12 | 240/170/24 |
| **α and near α alloys** | | | | | | | |
| Gr -12 | 12 (R53400) | 3.7105 | | | TiNiMo-Type 12 | | 480/350/18 |
| Ti-6Al-2Sn-4Zr-2Mo | (R54620) | 3.7145 | BT-25 BT-18y | | | | 900/830/10 |
| Ti-5Al-2,5Sn (Gr-6) | 6 -(R54520) | 3.7115 | BT5-1 | | TiAl5Sn2,5-Type6 | | 830/790/10 |
| Ti-5Al-2,5Sn ELI | (R54521) | | BT5-1кт | | | | 720/690/10 |
| Ti-8Al-1Mo-1V | (R54810) | | BT-14 | | | | 930/830/10 |
| Ti-6Al-2Sn-4Zr-2Mo (+Si) | (R54620) | 3.7145 | | | | | 1000/830/10 |
| **α – β alloys** | | | | | | | |
| Gr -5 | 5 (R56400) | 3.7165 | BT-6 | 10,11,12, 28,56,59 | TiAl6V4-Type5 | Class 60 | 900/830/10 |
| Gr -5ELI | (R56401) | | BT-6C | | TiAl6V4ELI-Type 5.1 | | 830/760/10 |
| Ti–4Al–4Mo-2,5Sn | - | 3.7185 | | 45,57,57 | | | 1100/960/9 |
| Ti-3Al-2,5V (Gr-9) | 9 (R56320) | 3.7195 | ПТ-3В | | TiAl3V2,5-Type9 | Class 61 | 620/520/15 |
| Ti-3Al-2,5V with Ruthenium (Gr-28) | 28 (R56323) | | | | | | 620/480/15 |
| Ti-6Al-4V ELI with Ruthenium (Gr-23) | 23 (R56407) | | | | | Class 60 E | 860/800/10 |
| Ti-6Al-6V-2Sn | (R56620) | 3.7175 | | | | | 1030/970/10 |
| Ti-6Al-2Sn-4Zr-6Mo | (R56260) | | | | | | 1170/1100/10 |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | (R58650) | | | | | | 1165/1110/10 |
| Ti-7Al-4Mo | (R56740) | | BT-8 | | | | 1030/970/10 |
| **β alloys** | | | | | | | |
| Ti-10V-2Fe-3Al | (R54610) | | | | | | 1190/1100/9 |
| Ti-3Al-8V-6Cr-4Mo-4Zr (Gr-19) | (R58640) | | | | | | 790/760/15 |
| Ti-13V-11Cr-3Al | | | TC6 | | | | 1170/1100 |

ASM – Aerospace Specifacation Metals; UNS - Unified Numbering System
ASTM – American Society for Testing and Materials; BS - British Standards
DIN - German Institute for Standardization; GOST -Russian Interstate standard
UNI – Italian Organization for Standardization; JIS – Japanese Industrial Standards

Titanium alloys are classified in several different ways:

1. According to the method of obtaining - deformable and molded;
2. According mechanical properties - alloys with low strength and high ductility, tensile alloys with medium and high strength alloys;
3. According to the terms of application - cold resistant, refractory and corrosion;
4. According to their ability to hardening with the use of thermal processing – strengthened and non - strenghtened;

5. According to their microstructure in annealed condition - alpha and alpha near alloys (the structure is fully alpha or 5% beta phase), alpha - beta and beta alloys (the structure is a stable beta phase).

Differences in mechanical properties of different brands technically pure titanium (Table. 1) are mainly due to the different maximum levels of the elements forming interstitial solid solution - mainly oxygen and besides him and carbon, hydrogen and nitrogen. The latter is the most effective element of a reinforcing titanium alloy, followed by oxygen.

Some alloys are with additional indication "ELI" (Tab. 1). They are manufactured with extremely low contents of harmful impurities for the use mainly in cryogenic equipment, where they are necessary to have good ductility and toughness.

As with the alloying of the steel, the alloying elements of titanium (forming substitution solid solution) are dissolved predominantly in one or other of its modification and influence on the polymorphic transformation [27].

For example, the addition of aluminum stabilizes the alpha phase and raises the temperature of polymorphic conversion (almost all industrial titanium alloys are alloyed with aluminum). Chromium, molybdenum and vanadium stabilize the beta phase and decrease the temperature of polymorphic transition. With a large amount of beta-stabilizers, the phase is stable at room temperature and below. Alloying elements also affect the rate of conversion from one phase to another.

The availability of the beta phase influences the behavior of titanium alloys which leads to: refining grains and increasing the strength; improves workability by hot plastic deformation; it allows the application of heat treatment; increases resilience; lowers weldability.

Alpha and near alpha alloys are not subject to a thermal treatment for increasing the strength. They have medium strength and creep resistance at elevated temperatures. For example, Gr-7 and Gr-12 have better corrosion resistance compared to Gr-1 and Gr-2.

The alpha-beta alloys are subject to strenghtened by homogenizing annealing and aging. They have an increased toughness in an annealed condition and high strength in heat-treated condition. The most commonly used alloys in this group are Gr-5 and Gr-5ELI.

Beta alloys contain a large amount of beta stabilizers, but in practice are not monophase. They are subject to annealed by aging, which leads to a significant increase of their strength, but they have low ductility and toughness. These alloys are strenghtened in deformation, and therefore are used as fasteners and springs.

Alpha and beta titanium alloys represent approximately 26% and 4% respectively of the market for these products in the US, while alpha-beta alloys occupy about 70%. Titanium alloy Ti-6Al -4V (Gr-5, Gr-5ELI) is of the latter category and covers 56% of the entire market for titanium and titanium alloys in the US [15].

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.

Titanium and its alloys are used in a wide range of areas as their selection may be based on corrosion resistance or strength characteristics [9], biocompatibility and others. [2]. These materials are most - widely used in the aerospace, automotive and medicine.

Aerospace industry is the main area of their application [24] and in particular in the systems of engines and hulls where it covers 36% and 7% [21]. In the US, about 70 to 80% of all orders for titanium alloys are for the aerospace industry [10]. The main reasons are: weight loss (mainly as replacement of the steel, but also as a replacement of Al); operating temperature (replacement of Al, Ni, alloy steel); corrosion resistance (replacing the Al and low-alloy steels) [5]. In the table - below (Table 2) are listed parts which are made of titanium alloys.

As the strength of titanium alloys is considerably higher than that of aluminum alloys, the parts can have a smaller cross-section, which leads to weight saving. The substitution of Al alloys with Ti alloys can also be carried out when the operating temperature exceeds that of the Al alloys - 130°C [5].

Tab. 2 Application of titanium alloys in the aerospace industry

| Alloy | Application |
|---|---|
| Ti-3Al-2.5V (Gr-9) | Used for hydraulic high pressure lines, replacing the stainless steel pipe and thus reducing the weight by 40%. It is used for the production of cell structures. |
| 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. |
| 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 ° C, in the high pressure compressors. |
| 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 surfaces, as well as the structure for the support on the floor. |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr + Si | Used for F22 program for Lockheed / Boeing. |
| Ti-6Al-2Sn-4Zr-6Mo | It is used at temperatures up to about 315 ° C, primarily for military engines, such as F-100 and F-119, with yield strength of 1035 MPa. |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | It is used at temperatures below 400 ° 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 | Almost the whole main landing gear of Boeing 77 is produced from this alloy which leads to a weight saving of about 270 kg per airplane. |

The use of titanium and titanium alloys in the automotive industry began with racing cars of Formula 1 in 1980, as the main application is for parts for engines [25]. However, due to the high cost of these materials their application in the automotive industry is limited. In recent years, however, titanium and its alloys have been intensively used for various automobile parts [13] presented in Table 3 [13, 18, 25].

Tab. 3 Application of titanium and titanium alloys in the automotive industry

| Alloy | Application |
|---|---|
| Ti-6Al-4V | Spring suspension, bumper, exhaust valves, connecting rods |
| 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 |

Titanium alloys are widely used in biomedical implants. [24] The use of titanium alloys as biomaterials is due to their reduced elasticity, high biocompatibility and increased resistance to corrosion compared to conventional stainless steel and Co-Cr alloys [32]. Technically pure titanium (Gr-1, 2, 3, 4) and alloy Ti-6Al-4V are the most widely used titanium materials in medicine [2].

The data presented in [1, 2, 6, 12] show the application of these materials in various fields of medicine for dental implants, hip and knee prostheses, trauma-fixing equipment (nails, screws), medical instruments, heart valves, pacemakers and many other [11]. Recently in this field some beta alloys without vanadium, and aluminum as Ti-6Al-7Nb and Ti-5Al-2.5Fe, Ti-13Nb-13Zr, Ti-12Mo-6Zr-2Fe are widely used [2]. Besides better biocompatibility, they have the additional advantages over the Ti-6Al-4V, such as a high strength wear and a lower modulus of elasticity [15].

## CONCLUSIONS

The data presented in the classification, properties and application of titanium and its alloys allow making the following important conclusions:

1. The use of titanium and titanium alloys in recent years has increased significantly due to the development of methods related to their production, further processing and their advantages over other materials.
2. The basic classification of titanium alloys is according to their microstructure in the annealed state, and on the basis of this they are divided into alpha and near alpha alloys, alpha - beta and beta alloys. Those with additional indication "ELI" are produced with extremely low content of harmful impurities and are used primarily in cryogenic equipment.
3. Nowadays more than 100 species of titanium alloys are known and only 20 ... 30 of them find practical application. About 70% of the used titanium alloys in US belongs to the group of alpha-beta alloys, as 56% of the total consumption is of the alloy Ti-6Al -4V (Gr-5, Gr-5ELI), which makes it the most widely used material based on titanium.
4. Titanium and its alloys are used in a number of areas, as the main customers are aerospace, automotive and medicine.

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**Contacts:**

Assoc. prof PhD Danail Gospodinov, Department of Materials science and Technology, University of Ruse, e-mail: dgospodinov@uni-ruse.bg

PhD Nikolay Ferdinandov, Department of Materials science and Technology, University of Ruse, e-mail: nferdinandov@uni-ruse.bg

Eng. Stoyan Dimitrov, PhD student, Department of Materials science and Technology, University of Ruse, e-mail: sdimitrov@uni-ruse.bg