Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials
Vol. 32, No. 1, February, 2022, pp. 11-16
Journal homepage: http://iieta.org/journals/rcma

Mechanical, Corrosion Resistance Properties and Various Applications of Titanium and Its Alloys: A Review

Kunle O. Babaremu[1*], Tien-Chien Jen[1], Philip O. Oladijo[1,3], Esther T. Akinlabi[1,2]

[1] Mechanical Engineering Department, University of Johannesburg, Johannesburg 2006, South Africa
[2] Directorate of Pan African Universities for Life and Earth Institute, Ibadan 200132, Oyo State, Nigeria
[3] Department of Chemical, Materials and Metallurgical Engineering, Botswana International University of Science and Technology, Palapye, Private Bag 16, Botswana

Corresponding Author Email: kunle.babaremu@paulesi.org.ng

https://doi.org/10.18280/rcma.320102

Received: 1 September 2021
Accepted: 13 October 2021

Keywords:
titanium, corrosion, alloys, strengthening, materials

ABSTRACT

Titanium (Ti) alloys have been employed for several structural purposes due to high strength, lightweight, temperature toughness, outstanding corrosion resistance and extreme temperature tolerance ability. However, their application for aircraft, military equipment and spacecraft etc. is limited by the exorbitant cost of raw materials and processing. Although, commercially unadulterated titanium exhibits satisfactory mechanical characteristics and has been used for some engineering applications. For many applications, titanium is combined or alloyed with little percentages of alloying elements such as vanadium and aluminium by weight. The combination possesses solid solubility which differs with temperature, enabling it to experience precipitation strengthening. This strengthening effect and effect of heat treatment does not only affect the mechanical and structural properties but alters the tribological and corrosion resistance (CR) properties of the alloys. The CR property of alloys is vital in any structural application and this affects other properties directly or indirectly. Therefore, this review paper examines the properties, classification and applications of Ti and its alloys.

1. INTRODUCTION

In recent years, there has been a paradigm shift towards the use of lightweight materials with other indispensable properties such as hardness, wear and corrosion resistance for structural and advance applications [1]. Titanium is a relatively low-density material, approximately two-third the density of iron [2]. It can be highly reinforced by deformation processing and alloying. Titanium is known for outstanding thermal and nonmagnetic characteristics. It exhibits a coefficient of thermal expansion relatively lower than that of steels, but somewhat lower than that of aluminium [3]. The usefulness of titanium and its alloys for high-temperature application is due to its high melting point of about 1943 K (1670℃), which is higher than those of steels [4]. However, for structural applications, their utmost useful temperature generally ranges from 698 to 868 K (425 to 595℃). Moreso, titanium alloys with aluminium as the predominant alloying element have shown promising application temperatures up to about 1033 K (760℃) [5]. These properties have made titanium and its alloys standout among several structural and high-temperature materials of choice.

Moreover, the excellent corrosion resistant properties of titanium and its alloys have been attributed to their ability to get passivated, and hence possesses a high level of immunity to the attack by chlorides and most mineral acids [6]. They are also non-toxic and usually biologically well-suited with human bones and tissues [7]. The blend of high strength, good toughness, stiffness, low density and outstanding corrosion resistance offered by different titanium alloys at extremely low to high temperatures enables weight savings in aircraft structures and many other high-performance and advanced applications [8]. The exceptional biocompatibility and corrosion resistance together with superior strength make titanium and its alloys valuable in petrochemical and chemical applications, biomaterials and marine environments [9].

The chemical industry is one of the major users of titanium as a result of its outstanding corrosion resistance, predominantly when they come in contact with oxidizing acids. The next largest user of Ti and its alloys is the aircraft industry mainly due to their cryogenic and ability to withstand high temperature [10]. The ballistic characteristics of titanium and its alloys are also exceptional on a weight-standardize basis [11]. Despite the significance of Ti and its alloys, limited articles exist that addressed the basic subjects in details. As the focus of this study is to concisely review properties of Ti and its alloys by considering useful classifications and applications, it is of immense necessity to understudy the potential applications of titanium and its alloy for other discoverable grey areas for future research in various field of human endeavour.

1.1 Classifications of titanium alloys

There are generally four classifications of titanium alloys. They are alpha (α) alloys, near alpha (α) alloys, alpha-beta (α-β) alloys, β-near β alloys [12]. Titanium α-alloys are made up of entirely α-phase. They contain elements like zirconium, tin e.t.c, and/or α-stabilisers like carbon, Al, nitrogen and oxygen. In most cases, they have aluminium as the main alloying element and stabilizing α-phase. An example of α alloys is Ti-5Al-2.5Sn [13]. The near α alloys contain ductile β-phase in small quantity. Apart from the α-phase stabilisers constituents in near α alloys, they also alloyed with about 1 to 2 percent of β-phase stabilisers such as silicon, molybdenum, vanadium, niobium, chromium and tungsten. Examples of near α alloys are Ti-6Al-2Sn-4Zr-2Mo-0.1Si, Ti-6Al-2Sn-4Zr-2Mo, Ti-8Al-1Mo-1V and Ti-5Al-5Sn-2Zr-2Mo [14-16]. The α-β alloys are metastable and usually consist of some blend of both α and β-stabilisers, and are generally heat treatable. Examples of α-β alloys of titanium are Ti-6Al-4V and Ti–6Al–6V–2Sn [17, 18]. The β-near β alloys are also metastable with adequate β-stabilisers such as Si, Mo and V. These stabilisers enable them to sustain the β phase when quenched. Their strength can also be enhanced through aged and solution heat treatment. Examples of β-near β alloys are Ti–29Nb–13Ta-4.6Zr, Ti25Nb3Mo3Zr2Sn, Ti-13Mo-7Zr-3Fe and Ti-10V-2Fe-3Al [19, 20].

Table 1. Grades of titanium and its alloys [21-25]

Grade	Alloy constituent	Properties
1	Pure Ti	Soft, ductile, corrosion resistance
5 (Ti-6Al-4V)	maximum of 0.2% O and 0.25% Fe, 4% V, 6% Al	Higher-strength than pure titanium, but have the same thermal and stiffness characteristics, heat treatable, a combination of outstanding strength, corrosion resistance, and fabricability
6 (Ti-5Al-2.5Sn)	2.5% Sn, 5% Al	Exhibits strength and Stability at high temperatures, excellent weldability
7	0.12-0.25% of palladium	Resistance to crevice corrosion at low temperatures and elevated pH
9	2.5% V and 3% Al	High strength and enhanced corrosion resistance, weldability
16	0.04-0.08% palladium	Improved corrosion resistance
18	3% Al, 2.5% V and 0.04 to 0.08% palladium	Palladium enhanced CR, High strength, weldability
23	Maximum of 0.13% O, 4% V, 6% Al	O and Fe enhance ductility and fracture toughness, reduces strength to some extent

Titanium and its alloys are also classified and supplied in ASTM grades as shown in Table 1. The grade is a function of the treatment required. For instance grades 5 and 23 are aged or annealed; grades 9 and 18 are annealed or stress-relieved and cold-worked. Other grades exist from 1 to 38 and have their compositions and properties. For instance grade 1 is regarded as the softest and most ductile Ti alloy. It is a superior material for cold forming and surroundings that are corrosive. Grade 2 is unalloyed Ti with a standard amount of oxygen, while grade 2 is also unalloyed Ti but contains medium oxygen. Generally, grades 1 to 4 are unalloyed and are considered commercially unadulterated [26, 27]. As the grade number increases, the yield and tensile strength increase for the unadulterated grades. The variation in their characteristics is largely due to the amount of constituting interstitial elements. They are employed for CR purposes in situations where cost, simplicity of production, and welding are essential.

2. ESSENTIAL PROPERTIES OF TITANIUM ALLOYS

2.1 Alpha (α) and near α alloys

Some literature has divided α-alloys into three subgroups based on their properties. They are (a) the single-phase α alloys, whose strength is due to solute hardening, (b) near α alloys containing up to 2 percent of a few β-stabilizing elements and could be forged, and also heat-treated in some other phase fields, (c) those titanium alloys which respond to traditional age-hardening treatment [28]. The most commonly employed single-phase α material is the commercially unadulterated titanium, which is majorly a Ti-O alloy. Pure titanium is solution-hardened by the addition of a regulated proportion of oxygen, which dissolves interstitially in the metallic material. Improved strengths are accomplished by substitutional solid solution hardening. A good example is a Ti-5Al-2.5Sn alloy [29].

Among all the titanium alloys, the near-α alloys exhibit the most superior creep resistance above 400°C and have outstanding characteristics that enable their application in gas turbines for a compressor disc alloy. Ti–6Al–5Zr–0.5Mo–0.25Si is a typical example [30]. Near-α alloys are applicable for high-temperature applications between approximately 500 to 550°C, where the combination of higher strength and excellent creep resistance is required [31]. These significant properties are due to small quantities of dispersed β-phase. Small quantities of vanadium and molybdenum content enable the retention of β-phase at ambient temperature. However, due to the high aluminium content in near α alloy like Ti-8Al-1Mo-1V, stress corrosion cracking becomes a challenge [32]. Hence, most alloys used in recent time are restricted to 6 percent weight of aluminium to prevent the challenges of stress corrosion cracking. Although this alloy exhibits a limited measure of hardenability due to a minute quantity of β-phase but possesses good weldability. Figure 1 shows the phase diagrams of single-phase α and near α alloys. Titanium alloys such as Ti-2.5Cu such as respond to traditional age-hardening treatment, and could be hardened in the process. This often results in the precipitation of a well-dispersed phase of Ti2Cu [33, 34]. The strength can be improved further by cold working the alloy before ageing.

2.2 Beta (β) and alpha-beta (α-β) titanium alloys

Beta titanium alloys have body centred cubic allotropic. They contain varying amount of iron, tantalum, copper, molybdenum, nickel, cobalt, copper, vanadium, niobium, chromium and zirconium [35]. In general, β-phase titanium exhibits higher ductility compared to α-phase. However, the α-phase is stronger due to the larger amount of slip planes in the body-centred cubic structure of the β-phase compared to the hexagonal closed packed α-phase. α-β phase Ti has mechanical characteristics which are in between the α and the β-phase titanium as shown in Figure 1 below [36, 37].

2.3 Response of titanium alloys to heat treatment

Like most alloys, titanium alloys are made to undergo heat treatment such as ageing and solution treatment to improve strength, and to enhance specific characteristics such as fatigue strength, corrosion resistance, creep strength at high temperature and fracture toughness [38]. The properties of Ti alloys of the α and near α phases cannot be appreciably improved by heat treatment. However, annealing and stress relief are being employed to enhance their performance characteristics, dramatically. The microstructure of α alloys are generally not significantly manipulate-able by heat treatment because the alloys do not experience any notable phase change. This reason makes it difficult to strengthen these alloys by heat treatment. Hence, annealing and stress relief continue to be a feasible alternative to strengthening titanium alpha and near α alloys [39]. The properties of β alloys cannot only be improved by annealing or stress relief, but also by ageing and solution treatment. The properties of α-β titanium alloys, which are alloys containing both alpha and beta phases at ambient temperature can be manoeuvred to a certain extent through heat treatment. This will involve the manipulation of their sizes, phase distributions and compositions. By heat-treating or working α-β titanium alloys above or below the α-β transition temperature, significant microstructural transformations can be accomplished [40]. This microstructural revolution could affect the strength of the material drastically.

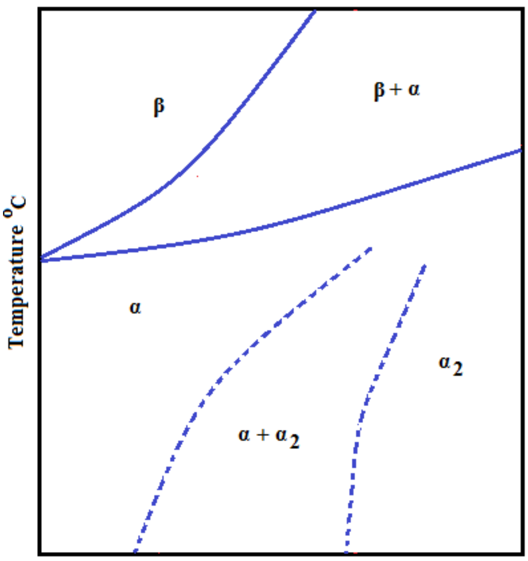

Figure 1. Phase diagrams of single-phase α and near α alloys

3. APPLICATIONS OF T_i AND ITS ALLOYS

Titanium is often used in aviation industries due to its CR properties, outstanding heat resistant properties, high strength and lightweight compared with steel. Ti alloys have been used largely for the production of metal orthopaedic joint substitutions, surgeries of plate bone and dental implant applications [41]. Different grades of titanium alloys are used for several applications. For instance, titanium alloys of grade 5 (Ti-6Al-4V) have found applications in Cases, blades, discs, fasteners, rings, biomedical implants, forgings vessels, hubs and airframes [42]. The grade 6 (Ti-5Al-2.5Sn) of titanium alloy are also applied in jet engines and airframes. Due to the presence of a small amount of palladium in Grade 7 alloys, which enhances its resistance to crevice corrosion, it is used for the fabrication of screws, bolts and nuts. More often, grade 9 titanium alloy is used for the manufacture of sporting equipment and aircraft tubing for hydraulics, while grade 23 (Ti-6Al-4V-ELI) is the predominantly used medical implant Ti alloy grade [43].

Young's modulus determines the stiffness of materials. Their value is directly related to the atomic bonding in the crystal lattice and thus rises with its level of ordering. Titanium alloys show a modulus of elasticity which is somewhat low. It is approximately half that of nickel alloys and steels [44]. This increased elasticity or flexibility implies reduced cyclic and bending stresses in deflection-controlled functions, making titanium alloys ideal for bellows, springs, dental fixtures, body implants, drill pipe, sports equipment and dynamic offshore risers. Asides from artificial joints, bones and dental implants, titanium and its alloys are frequently used in osteosynthesis, like bone fracture-fixation [45]. According to some authors, a bone fracture hinders the performance of the wounded limb [46]. Timely and full reinstatement can be accomplished by osteosynthesis, a technique of treating bone fracture through surgical means.

3.1 Automobile Industry

Titanium gained early recognition in the automotive industry in the year 1980 through the use of Formular 1 car used for racing. Titanium and titanium alloys were used out of sensitivity for the engine parts. Further into the new age of technological advancement and development in the design of cars, Ti and its alloys are now used for various parts of vehicles like bumpers, exhaust system, spring suspension, connecting rod, exhaust valve, fuselage and body [47].

3.2 Medical Industry

Titanium and its alloys also have wide relevance in the field of medicine for biomedical implants which makes titanium a very reliable biological material. This is owing to certain defining qualities of Ti such as immense biocompatibility, reduced elasticity corrosion resistance which is better than other materials like Co-Cr alloys and stainless steel [47, 48]. Some os the specific application of titanium in medicine are heart valves, knee and hip prostheses, dental implants, medical instruments and many more. The suitability of titanium in the medical field is well pronounced in the area of metal implants where there is direct contact with bones and flesh tissues [48].

3.3 Aerospace Industry

Majorly, the required materials for aerospace applications also depend on good resistance to embrittlement when the operating temperature is low, resistance to high temperatures, low density, resistance to thermal expansion and corrosion [49]. More also, as compared to most other metals like aluminium and steel, titanium has better stability at very high temperatures, higher corrosion resistance, and specific strength. Titanium started gaining proper recognition in the aerospace industry in the early 1940's owing to its light weight advantage which is a very significant consideration in the aerospace industry. The major rationale for growth in the rate of utilization of titanium is its very strength to weight ratio with a density that falls in between iron and aluminum [50]. Titanium and its alloys are widely utilized in several industrial applications which includes fasteners, vessel, hubs, discs, rings and blades.

4. CONCLUSIONS

This article reviewed titanium and its alloys. The main aspects examined were classification, characteristics, response to heat treatment and applications. From the wide range of literature reviewed, it was discovered the titanium and its alloys were considered one of the promising materials for several engineering applications and other fields such as athletics and medicals. The desire for these materials was attributed to the outstanding corrosion resistance, high melting temperature and matchless blend of high strength-to-weight ratio. The major classification of Ti alloys is according to microstructure in the heat-treated annealed condition. Titanium alloys are divided into four groups, which are α alloys, near α alloys, α-β alloys, and β-near β alloys. Also, ASTM classified Ti alloys grade considering their alloying elements and properties. Many researchers have revealed that titanium and its alloys have been applied in several areas such as military, marine, sports, medical, automotive, petrochemical and aerospace. Although, automotive, military, aerospace and have been the largest consumer of the materials. However, a major limitation amongst others which is insufficient access to data and improved methodology. Hence, the future research direction in this area is to further explore the applications of titanium and its alloy through advanced methodologies for improved relevance.

ACKNOWLEDGMENT

The authors of this manuscript will like to appreciate the management of the University of Johannesburg for the financial support through URC funding towards making this research possible.

REFERENCES

[1] Ferreira, A.D.B., Nóvoa, P.R., Marques, A.T. (2016). Multifunctional material systems: A state-of-the-art review. Composite Structures, 151: 3-35. https://doi.org/10.1016/j.compstruct.2016.01.028

[2] Xiao, X., Lu, S.Q., Dong, X.J., Huang, M.G., Liu, J.W. (2011). The effect of titanium addition on microstructure and properties of laves phase cr_2nb alloy synthesized by hot pressing. In Advanced Materials Research, 328-330: 1102-1108. https://doi.org/10.4028/www.scientific.net/AMR.328-330.1102

[3] Markovsky, P.E., Akhonin, S.V., Berezos, V.A., Bondarchuk, V.I., Stasuk, O.O., Karasevska, O.P., Gavrysh, I.M. (2020). Microstructure and tensile properties of cost-efficient thermally hardenable α+ β alloys of Ti–Al–Mo–Fe and Ti–Al–Mo–Cr systems. Metallography, Microstructure, and Analysis, 9(6): 856-872. https://doi.org/10.1007/s13632-020-00705-7

[4] Attar, H., Ehtemam-Haghighi, S., Kent, D., Dargusch, M.S. (2018). Recent developments and opportunities in additive manufacturing of titanium-based matrix composites: A review. International Journal of Machine Tools and Manufacture, 133: 85-102. https://doi.org/10.1016/j.ijmachtools.2018.06.003

[5] Chatterjee, R., Murty, S.N., Alankar, A. (2019). Dynamic recrystallization in titanium alloys: A comprehensive review. Materials Performance and Characterization, 9(2): 1-42. https://doi.org/10.1520/MPC20190032

[6] Sasikumar, Y., Indira, K., Rajendran, N. (2019). Surface modification methods for titanium and its alloys and their corrosion behavior in biological environment: A review. Journal of Bio-and Tribo-Corrosion, 5(2): 1-25. https://doi.org/10.1007/s40735-019-0229-5

[7] Wally, Z.J., Van Grunsven, W., Claeyssens, F., Goodall, R., Reilly, G.C. (2015). Porous titanium for dental implant applications. Metals, 5(4): 1902-1920. https://doi.org/10.3390/met5041902

[8] Peters, M., Kumpfert, J., Ward, C.H., Leyens, C. (2003). Titanium alloys for aerospace applications. Advanced Engineering Materials, 5(6): 419-427. https://doi.org/10.1002/adem.200310095

[9] Balazic, M., Kopac, J., Jackson, M.J., Ahmed, W. (2007). Titanium and titanium alloy applications in medicine. International Journal of Nano and Biomaterials, 1(1): 3-34.

[10] Shokrani, A., Al-Samarrai, I., Newman, S.T. (2019). Hybrid cryogenic MQL for improving tool life in machining of Ti-6Al-4V titanium alloy. Journal of Manufacturing Processes, 43: 229-243. https://doi.org/10.1016/j.jmapro.2019.05.006

[11] Li, R., Fan, Q., Gao, R., Huo, L., Wang, F., Wang, Y. (2014). Effects of dynamic mechanical properties on the ballistic performance of a new near-β titanium alloy Ti684. Materials & Design (1980-2015), 62: 233-240. https://doi.org/10.1016/j.matdes.2014.05.044

[12] Guo, L., Fan, X., Yu, G., Yang, H. (2016). Microstructure control techniques in primary hot working of titanium alloy bars: A review. Chinese Journal of Aeronautics, 29(1): 30-40. https://doi.org/10.1016/j.cja.2015.07.011

[13] He, D., Zhu, J., Zaefferer, S., Raabe, D. (2014). Effect of retained beta layer on slip transmission in Ti–6Al–2Zr–1Mo–1V near alpha titanium alloy during tensile deformation at room temperature. Materials & Design (1980-2015), 56: 937-942. https://doi.org/10.1016/j.matdes.2013.12.018

[14] Wang, K., Wu, M., Yan, Z., Li, D., Xin, R., Liu, Q. (2018). Dynamic restoration and deformation heterogeneity during hot deformation of a duplex-structure TC21 titanium alloy. Materials Science and Engineering: A, 712: 440-452. https://doi.org/10.1016/j.msea.2017.11.127

[15] Tan, M.J., Chen, G.W., Thiruvarudchelvan, S. (2007). High temperature deformation in Ti–5Al–2.5Sn alloy. Journal of Materials Processing Technology, 192: 434-438. https://doi.org/10.1016/j.jmatprotec.2007.04.027

[16] Sinha, V., Schwarz, R.B., Mills, M.J., Williams, J.C. (2018). Effects of hydrogen on fatigue behavior of near-alpha titanium alloys. Scripta Materialia, 153: 81-85. https://doi.org/10.1016/j.scriptamat.2018.03.027

[17] Lindwall, G., Moon, K.W., Chen, Z., Mengason, M., Williams, M.E., Gorham, J.M., Zhao, J.C., Campbell, C.E. (2018). Diffusion in the Ti-Al-V system. Journal of Phase Equilibria and Diffusion, 39(5): 731-746. https://doi.org/10.1007/s11669-018-0673-9

[18] Shi, X., Zeng, W., Long, Y., Zhu, Y. (2017). Microstructure evolution and mechanical properties of near-α Ti-8Al-1Mo-1V alloy at different solution temperatures and cooling rates. Journal of Alloys and

Compounds, 727: 555-564. https://doi.org/10.1016/j.jallcom.2017.08.165

[19] Semiatin, S.L., Kirby, B.C., Salishchev, G.A. (2004). Coarsening behavior of an alpha-beta titanium alloy. Metallurgical and Materials Transactions A, 35(9): 2809-2819. https://doi.org/10.1007/s11661-004-0228-z

[20] Barriobero-Vila, P., Requena, G., Buslaps, T., Alfeld, M., Boesenberg, U. (2015). Role of element partitioning on the α–β phase transformation kinetics of a bi-modal Ti–6Al–6V–2Sn alloy during continuous heating. Journal of Alloys and Compounds, 626: 330-339. https://doi.org/10.1016/j.jallcom.2014.11.176

[21] Atapour, M., Pilchak, A.L., Frankel, G.S., Williams, J.C. (2011). Corrosion behavior of β titanium alloys for biomedical applications. Materials Science and Engineering: C, 31(5): 885-891. https://doi.org/10.1016/j.msec.2011.02.005

[22] Mellor, I., Grainger, L., Rao, K., Deane, J., Conti, M., Doughty, G., Vaughan, D. (2015). Titanium powder production via the Metalysis process. Titanium Powder Metallurgy, 51-67. https://doi.org/10.1016/B978-0-12-800054-0.00004-6

[23] Kumar, J. (2014). Investigations into the surface quality and micro-hardness in the ultrasonic machining of titanium (ASTM GRADE-1). Journal of the Brazilian Society of Mechanical Sciences and Engineering, 36(4): 807-823. https://doi.org/10.1007/s40430-014-0130-6

[24] Hama, T., Kobuki, A., Takuda, H. (2017). Crystal-plasticity finite-element analysis of anisotropic deformation behavior in a commercially pure titanium Grade 1 sheet. International Journal of Plasticity, 91: 77-108. https://doi.org/10.1016/j.ijplas.2016.12.005

[25] Elias, C.N., Lima, J.H.C., Valiev, R., Meyers, M.A. (2008). Biomedical applications of titanium and its alloys. Jom, 60(3): 46-49. https://doi.org/10.1007/s11837-008-0031-1

[26] Plaine, A.H., da Silva, M.R., Bolfarini, C. (2019). Tailoring the microstructure and mechanical properties of metastable Ti–29Nb–13Ta-4.6 Zr alloy for self-expansible stent applications. Journal of Alloys and Compounds, 800: 35-40. https://doi.org/10.1016/j.jallcom.2019.06.049

[27] Jackson, M., Dashwood, R., Flower, H., Christodoulou, L. (2005). The microstructural evolution of near beta alloy Ti-10V-2Fe-3Al during subtransus forging. Metallurgical and Materials Transactions A, 36(5): 1317-1327. https://doi.org/10.1007/s11661-005-0223-z

[28] Li, H., Mason, D.E., Yang, Y., Bieler, T.R., Crimp, M.A., Boehlert, C.J. (2013). Comparison of the deformation behaviour of commercially pure titanium and Ti–5Al–2.5 Sn (wt.%) at 296 and 728 K. Philosophical Magazine, 93(21): 2875-2895. https://doi.org/10.1080/14786435.2013.791752

[29] Hua, F., Mon, K., Pasupathi, P., Gordon, G., Shoesmith, D. (2005). A review of corrosion of titanium grade 7 and other titanium alloys in nuclear waste repository environments. Corrosion, 61(10): 987-1003. https://doi.org/10.5006/1.3280899

[30] Ahmed, Y.M., Sahari, K.S.M., Ishak, M., Khidhir, B.A. (2014). Titanium and its alloy. International Journal of Science and Research, 3(10): 1351-1361.

[31] Chakravarty, H.N. (2019). Effect of alloying additions of aluminium and iron on the creep resistance of Ti-12Cr (Wt.%). Michigan State University.

[32] Yadav, P., Saxena, K.K. (2020). Effect of heat-treatment on microstructure and mechanical properties of Ti alloys: An overview. Materials Today: Proceedings, 26: 2546-2557. https://doi.org/10.1016/j.matpr.2020.02.541

[33] Mahadule, D., Khatirkar, R.K., Gupta, A., Kumar, R. (2021). Effect of heating temperature and cooling rate on the microstructure and mechanical properties of a Mo-rich two phase α+β titanium alloy. Journal of Materials Research, 1-13. https://doi.org/10.1557/s43578-020-00100-6

[34] Wanjara, P., Jahazi, M., Monajati, H., Yue, S., Immarigeon, J.P. (2005). Hot working behavior of near-α alloy IMI834. Materials Science and Engineering: A, 396(1-2): 50-60. https://doi.org/10.1016/j.msea.2004.12.005

[35] Atapour, M., Pilchak, A.L., Shamanian, M., Fathi, M.H. (2011). Corrosion behavior of Ti–8Al–1Mo–1V alloy compared to Ti–6Al–4V. Materials & Design, 32(3): 1692-1696. https://doi.org/10.1016/j.matdes.2010.09.009

[36] Lincai, Z., Xiaoming, D., Wei, Y., Man, Z., Zhenya, S. (2018). Effect of prestrain on precipitation behaviors of Ti-2.5 Cu alloy. High Temperature Materials and Processes, 37(5): 487-493. https://doi.org/10.1515/htmp-2017-0006

[37] Cardoso, F.F., Cremasco, A., Contieri, R.J., Lopes, E.S.N., Afonso, C.R.M., Caram, R. (2011). Hexagonal martensite decomposition and phase precipitation in Ti–Cu alloys. Materials & Design, 32(8-9): 4608-4613. https://doi.org/10.1016/j.matdes.2011.03.040

[38] Kolli, R.P., Devaraj, A. (2018). A review of metastable beta titanium alloys. Metals, 8(7): 506. https://doi.org/10.3390/met8070506

[39] Li, C., Chen, J., Li, W., He, J.J., Qiu, W., Ren, Y.J., Chen, J.L., Chen, J.H. (2015). Study on the relationship between microstructure and mechanical property in a metastable β titanium alloy. Journal of Alloys and Compounds, 627: 222-230. https://doi.org/10.1016/j.jallcom.2014.12.100

[40] Ahmed, M., Wexler, D., Casillas, G., Ivasishin, O.M., Pereloma, E.V. (2015). The influence of β phase stability on deformation mode and compressive mechanical properties of Ti–10V–3Fe–3Al alloy. Acta Materialia, 84: 124-135. https://doi.org/10.1016/j.actamat.2014.10.043

[41] Yadav, P., Saxena, K.K. (2020). Effect of heat-treatment on microstructure and mechanical properties of Ti alloys: An overview. Materials Today: Proceedings, 26: 2546-2557. https://doi.org/10.1016/j.matpr.2020.02.541

[42] Sadeghpour, S., Abbasi, S.M., Morakabati, M., Bruschi, S. (2017). Correlation between alpha phase morphology and tensile properties of a new beta titanium alloy. Materials & Design, 121: 24-35. https://doi.org/10.1016/j.matdes.2017.02.043

[43] Chan, K.S., Koike, M., Mason, R.L., Okabe, T. (2013). Fatigue life of titanium alloys fabricated by additive layer manufacturing techniques for dental implants. Metallurgical and Materials Transactions A, 44(2): 1010-1022. https://doi.org/10.1007/s11661-012-1470-4

[44] Sani, A.S., Suleimanb, Y.I., Eyinavia, A.I. (2019). Classification, properties and applications of titanium and its alloys used in automotive industry - A review. International Journal of Precious Engineering Research and Applications (IJPERA), 4(3): 23-36.

[45] Sani, A.S., Suleimanb, Y.I., Eyinavia, A.I., Usmana, A.

(2019). Classification, Properties and Applications of titanium and its alloys used in aerospace, automotive, biomedical and marine industry- A review. American Journal of Engineering Research (AJER), 8(8): 92-98.
[46] Liu, X., Chu, P.K., Ding, C. (2004). Surface modification of titanium, titanium alloys, and related materials for biomedical applications. Materials Science and Engineering: R: Reports, 47(3-4): 49-121. https://doi.org/10.1016/j.mser.2004.11.001
[47] Gospodinov, D., Ferdinandov, N., Dimitrov, S. (2016). Classification, properties and application of titanium and its alloys. Proceedings of University of Ruse, 55(2): 27-32.
[48] Elias, C.N., Lima, J.H.C., Valiev, R., Meyers, M.A. (2008). Biomedical applications of titanium and its alloys. Jom, 60(3): 46-49. https://doi.org/10.1007/s11837-008-0031-1
[49] Williams, J.C., Boyer, R.R. (2020). Opportunities and issues in the application of titanium alloys for aerospace components. Metals, 10(6): 705. https://doi.org/10.3390/met10060705
[50] Gomez-Gallegos, A., Mandal, P., Gonzalez, D., Zuelli, N., Blackwell, P. (2018). Studies on titanium alloys for aerospace application. In Defect and Diffusion Forum, 385: 419-423. https://doi.org/10.4028/www.scientific.net/DDF.385.419