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INTEGRITET BIOMEDICINSKIH IMPLANTA OD LEGURA TITANA (PRVI DEO)
INTEGRITY OF BIOMEDICAL IMPLANTS OF TITANIUM ALLOYS (FIRST PART)

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Ključne reči
- legure titana
- biomedicinsko inženjerstvo
- biokompatibilnost
- integritet biomedicinskog implanta

Izvod

U radu su prikazane osnovne grupe metalnih materijala koje se koriste u medicini. sa posebnim osvrtom na primenu titana i legura titana u biomedicinskom inženjerstvu. Analizirana su osnovna svojstva koja metalni materijali moraju posedovati da bi se mogli primenjivati za izradu medicinskih implanata. Razvoj novih materijala koji bi omogućili manju interakciju implanta sa živim tkivima i tako produžili vek implantnih delova je posebno razmatran.

Keywords
- titanium alloys
- biomedical engineering
- biocompatibility
- integrity of biomedical implant

Abstract

In the paper metallic materials for medical applications are presented, with attention paid to titanium and titanium alloys for biomedical engineering application. Basic properties of metallic materials required for medical implant manufacturing are analyzed. The development of new materials capable to lowering the interactions between implant materials and living tissues which would prolong service life of implant parts is specialy considered .

UVOD

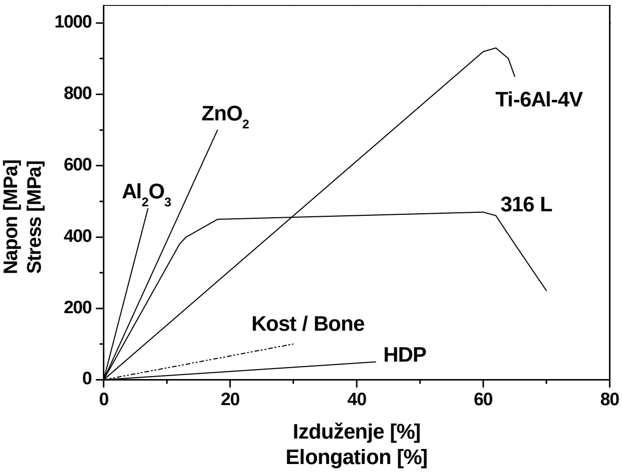
Poslednjih decenija materijali na bazi titana, zahvaljujući izvanrednim svojstvima, nalaze široku primenu u različitim granama industrije, uključujući biomedicinsko inženjerstvo. Visoka temperatura topljenja, mala gustina, dobra otpornost prema koroziji (sve do 500°C), kao i stabilnost mehaničkih svojstava u širokom intervalu temperatura (od 200 do 600°C) su osnovne karakteristike zbog kojih su titan i njegove legure važni konstrukcioni materijal široke primene, /1/. Inertan je u odnosu na običnu i morsku vodu, rastvore većine hlorida, razblažene rastvore alkalija, kao i rastvore sone i sumporne kiseline, što omogućava njegovu primenu u hemijskoj industriji. Titan je takođe pogodan za izradu cevovoda za prenos agresivnih tečnosti, za postrojenja u petrohemijskoj i naftnoj industriji, ali i onih delova koji dolaze u kontakt sa istopljenim metalima. Međutim, na temperaturama višim od 500°C titan je veoma hemijski aktivan. Zbog svoje sposobnosti da apsorbuje gasove, kao što su vodonik, azot i kiseonik, titan se široko koristi u elektronskoj industriji. Osnovna prednost titana u odnosu na druge metalne materijale je njegova izvanredna specifična čvrstoća (odnos čvrstoće i gustine), koja je četiri puta veća nego kod železa i šest puta veća od specifične čvrstoće aluminijuma, /1/. S obzirom da titan, ojačan legiranjem i termo-mehaničkom obradom, i dalje odlikuje mala gustina, legure titana se primenjuju u mašinogradnji, automobilskoj i avionskoj industriji i u kosmonautici, a zbog. termičke stabilnosti se koriste za izradu uređaja u energetici, kao što su delovi parnih turbina, kompresora i kondenzatora. Odlična mehanička svojstva i biološka inertnost titana i njegovih legura u odnosu na živi organizam, uz dobru korozionu postojanost, omogućila su njihovu primenu i kao biomaterijala za implante u medicini.

INTRODUCTION

Because of their outstanding properties, in the last few decades, titanium based materials are widely used in diverse industry branches, including biomedical engineering. High melting temperature, low density, high corrosion resistance (up to 500°C) and good mechanical characteristics in a wide temperature range (from 200 to 600°C) are the main characteristics that classify titanium and its alloys as important and widely used structural materials, /1/. Titanium is inert in the presence of plain and sea water, most chloride solutions, alkali solutions, as well as in chloric and sulphuric acid, enabling its use as structural material in chemical industry. In addition, titanium is convenient for aggressive liquids pipelines manufacturing, for equipment in petrochemical and oil industry, and also for components in contact with molten metal. Anyhow, at temperatures above 500°C titanium is extremely reactive. Due to its capability to absorb gases, such as hydrogen, nitrogen and oxygen, titanium is widely used in electronic industry. Major advantages of titanium, compared to other metallic materials, is its extraordinary specific strength (strength/densisy ratio), being four times higher than that of iron and six times higher than the specific strength of aluminium, /1/. Since titanium strengthen by alloying and thermo-mechanical treatment saved low density, titanium alloys are applied in mechanical engineering, automotive and airplane industries, and also in aerospace engineering, and due to thermal stability are used for manufacturing of energetics equipment, such as components of steam turbines, compressors and condensers. Excellent mechanical properties and biocompatibility of titanium and its alloys, combined with good corrosion resistance, enabled to use them as biomaterials for medical implants.

BIOKOMPATIBILNI METALNI MATERIJALI ZA PRIMENU U MEDICINI

Kao biometalni materijali ili biokompatibilni metalni materijali su definisanimetalni materijali koji se primenjuju u kontaktu sa ćelijama, tkivima ili telesnim tečnostima ljudskog organizma. Najčešće se koriste za zamenu ili nadogradnju strukturnih komponenti ljudskog organizma kako bi se nadomestila oštećenja do kojih dolazi zbog starenja, bolesti ili nesrećnih slučajeva. Zbog izuzetnih mehaničkih karakteristika (sl. 1) i dobre elektroprovodnosti, biokompatibilni metalni materijali se koriste za izradu medicinskih implanata, kao što su veštački zglobovi, stomatološki implanti, veštačka srca, spojnice, fiksacione pločice, žice i stentovi (sl. 2), ali i medicinskih elektronskih uređaja, pejsmejker elektroda i veštačko unutrašnje uho.



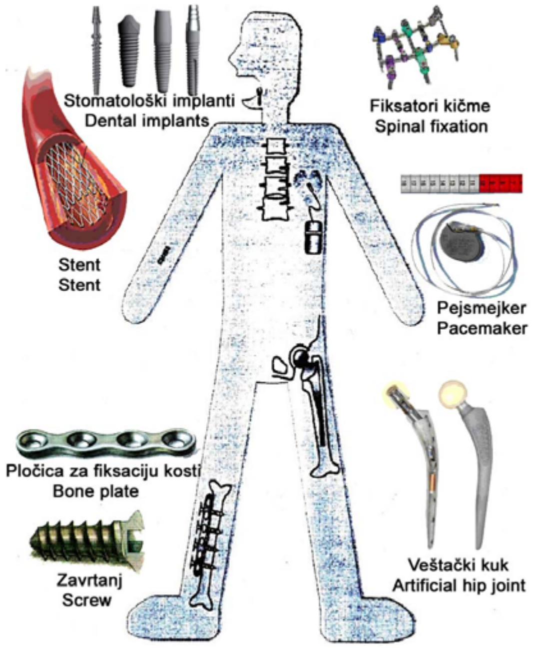
Slika 1. Karakteristične krive napon–izduženje za različite materijale.
Figure 1. Characteristic stress–elongation curves for different biocompatible metallic materials.

Nerđajući čelici, kobalt-hrom legure i legure titana su osnovni biokompatibilni metalni materijali koje se koriste u biomedicinskom inženjerstvu, /2/. Nijedna od navedenih legura nije osebno razvijena za primenu u ortopediji i biomedicini. Zbog njihove izuzetne čvrstoće i otpornosti prema koroziji, ispoljenih tokom primene u avio industriji, astronautici, brodogradnji i hemijskoj industriji, došlo je do ideje da bi se ti materijali mogu koristiit i za medicinske implante. Međutim, metalni implanti imaju i neke nepoželjne karakteristike i mane, kao što su krutost veća od krutosti kojom se odlikuje kost, velika specifična težina i nepropusnost X-zraka, zbog čega je njihov dalji razvoj od primarnog značaja za njihovu buduću primenu u medicini.

Čelični materijali su počeli da se koriste za izradu pločica i zavrtnja za fiksaciju polomljenih kostiju već tokom devetnaestog veka. Primena čelika u ortopediji omogućila je bolju fiksaciju naprslih kostiju nego što je to ranije bio slučaj kada su za fiksaciju korišćene metalne žice.

BIOCOMPATIBLE METALLIC MATERIALS FOR MEDICAL APPLICATION

Biometallic materials, or biocompatible metallic materials, are defined as metallic materials which are used in contact with cells, tissues or human body fluids. Most commonly, these materials are implanted into human bodies to compensate the structural components loss of shape or function, that originates from aging, diseases and accidents. Because of their exceptional mechanical characteristics (Fig. 1) and exceptional electroconductivity, biocompatible metallic materials are often used for production of diverse medical implants, such as artificial joints, dental implants, artificial hearts, bone plates, staples, wires and stents (Fig. 2), as well as for electronic devices, such as pacemaker electrodes and artificial inner ears.



Slika 2. Medicinski implanti izrađenii od metalnih materijala
Figure 2. Medical implants made of metallic materials.

Stainless steels, cobalt-chromium alloys and titanium alloys are the base biocompatible metallic materials used in biomedical engineering, /2/. None of these alloys were developed specifically for orthopaedic or biomedical applications. Instead, their proven strength and corrosion resistance experienced in the airplane, aerospace, marine and chemical industries, have led to the idea that these materials could be used as medical implant materials. However, metallic implants also show some undesired characteristics and disadvantages that include excessively high rigidity when compared to human bone, high specific gravity and shielding of X-rays, whereupon their further development is of high importance for future medical applications.

During the nineteenth century, use of steel materials as bone plates and screws for fracture fixations began. Application of steel fixations in the field of orthopaedics allowed a stronger fixation of broken bones than the earlier method of fixation which included use of metallic wires.

Zbog korozije, koja se javla u ljudskom telu, prvobitno korišćene čelike prevučene niklom i legirane vanadijumom su zamenili ugljenični čelici. Međutim, ni ugljenični čelici nisu bili dovoljno koroziono postojani, što je i uslovljavalo njihov toksični uticaj na ljudski organizam. Istraživanja u oblasti biokompatibilnih metalnih materijala su doprinela razvoju nerđajućih čelika, kobalt-hrom-molibden legura (npr. vitalijum) i legura titana, koji su postepeno postali osnovni biokompatibilni medicinski materijali za primenu, kako u ortopediji, tako i u drugim granama medicine.

Nerđajući čelik, pre svega 18Cr-8Ni čelik, je kao ortopedski materijal počeo da se koristi sredinom dvadesetih godina prošlog veka. Međutim, ubrzo je postalo jasno da je njegova upotreba praćena problemima korozije i zamorne čvrstoće, zbog je zamenjen sa 17Cr-14Ni-2,5Mo nerđajućim čelikom, koji je pokazao veću otpornost prema koroziji u hloridnoj sredini, kakvu predstavlja ljudski organizam. Vitalijum je pak razvijen sredinom treće decenije prošlog veka. Kasnije je otkriveno da je ova legura vrlo otporna prema koroziji i habanju, što je dovelo do široke primene u izradi spojeva veštačkog kuka i materijala za veštačke kosti.

Titan je izuzetno reaktivan element, koji se u zemljinoj kori nalazi u vidu stabilnog oksida, što samo potvrđuje činjenicu da je metalni titan i kiseonik teško razdvojiti. Iz tog razloga je titan tek krajem četvrte decenije prošlog veka ušao u komercijalnu upotrebu u SAD. Iako je titan u medicinske svrhe počeo da se upotrebljava znatno kasnije nego drugi metalni biokompatibilni materijali, njegova upotreba u medicinske svrhe ubrzo je značajno uvećana zahvaljujući njegovim izuzetnim svojstvima kao što su: relativno visoka specifična čvrstoća, nizak Jangov modul, velika biokompatibilnost i izuzetno nizak nivo toksičnosti, pogotovo kada se uporedi sa nerđajućim čelikom i vitalijumom. Krajem XX i početkom XXI veka, osnovne komercijalne forme titana u biomedicinskom inženjerstvu postale su komercijalno čist (CP) titan i legura Ti-6Al-4V.

Za izradu hirurških alata i eksternih fiksatora i dalje se koriste jeftiniji varijeteti nerđajućih čelika i aluminijumskih legura, dok su za punjenje dentalnih kaviteta, zlato, olovo i kalaj, zamenjeni srebro-živa amalgamima i srebro-kalaj amalgamima. U prvoj polovini XX veka vitalijum je u stomatologiji zamenio plemenite metale kao legura za izradu zubnih proteza da bi, u drugoj polovini XX veka, to bile legure titana.

KARAKTERISTIKE METALNIH MATERIJALA ZA PRIMENU U BIOMEDICINSKOM INŽENJERSTVU

Biokompatibilni metalni materijali, koji se koriste za izradu medicinskih implanata, moraju zadovoljavati određene kriterijume i posedovati sledeća svojstva:

Netoksičnost: Netoksičnost je izuzetno bitna karakteristika implantnih materijala s obzirom da oslobađanje metalnih jona i drugih produkata može uticati na pojavu raka, deformiteta, alergija, nekroza, kalcifikacija i zapalenjskih procesa, /3/.

Izuzetna otpornost prema koroziji: U idealnom slučaju biokompatibilni metalni materijali ne bi trebalo uopšte da korodiraju kada se nalaze u dodiru sa živim tkivima pošto je njihova korozija u velikoj meri povezana, kako sa toksičnošću materijala, tako i sa izdržljivošću materijala koji se nalazi u ljudskom organizmu.

Due to corrosion, occurred in the human body, initially used nickel-plated and vanadium-based steels were replaced with carbon steels. However, carbon steels were not sufficiently resistant to corrosion which had lead to their toxicity inside the human body. Long-term researches in the field of biocompatible metallic materials contributed to the development of stainless steels, cobalt-chromium-molybdenum alloys (e.g. vitallium), and of titanium and titanium alloys, which all gradually became the main biomedical materials used in orthopaedics and in other medical fields.

Stainless steel, principally 18Cr-8Ni steel, was used as an orthopaedic material since the second decade of the XX century. However, soon it became clear that its use was accompanied with problems caused by corrosion and fatigue strength, which consequently resulted in its replacement with 17Cr-14Ni-2.5Mo stainless steel, that proved to be more corrosion resistant to chloride environment such is the human body. Vitallium was developed in mid thirties of the last century. Later it was found that this alloy is highly corrosion and wear resistant, which led to its wide use as artificial hip joints and artificial bones material.

Titanium is an extremely reactive element, found in the earth’s crust as a stable oxide, which only confirms the fact that metallic titanium and oxygen are not easily separated. Owing to this, it was not until the mid of the last century that titanium found use in commercial applications in the USA. Although use of titanium for medical applications began later than other biocompatible metallic materials, its use as a biometallic material soon increased due to its favourable properties: relatively high specific strength, low Young’s modulus, high biocompatibility and low toxicity level (especially compared to stainless steel and vitallium). By the end of the XX and at the beginning of the XXI century the main commercial forms of titanium in biomedical engineering are commercially pure (CP) titanium and Ti-6Al-4V alloy.

Surgical tools and external fixtures are still produced of cheaper varieties of stainless steels or aluminium alloys, while silver-mercury amalgam and silver-tin amalgam replaced gold, lead and tin for dental cavity fillings. In the first half of the XX century, vitallium replaced precious metals as an alloy used in dentures, while titanium alloys followed in the second half.

CHARACTERISTICS OF METALLIC MATERIALS USED IN BIOMEDICAL ENGINEERING

Biocompatible metallic materials used as medical implant materials must fulfil certain criteria and possess following properties:

Nontoxicity: Nontoxicity of the implant materials is one of essential material characteristics, since the release of metallic ions and other products can lead to cancer, deformities, allergies, necrosis, calcification and inflammation processes, /3/.

High corrosion resistance: Ideally, biocompatible metallic materials should not corrode at all in direct contact with living tissues since their corrosion is very much related to both the citotoxicity of the material, and to the durability of the material inside the human body.

Izdržljivost: Materijali usađeni u ljudski organizam u vidu implanata bi tokom celog svog radnog veka trebalo da funkcionišu bez ikakvih oštećenja, što podrazumeva njihovu izuzetnu zamornu čvrstoću pri koroziji i zamornu čvrstoću pri trenju i koroziji, ali i minimalno oslobađanje čestica prilikom pojave trenja i habanja, /4, 5/.

Čvrstoća i žilavost: Dimenzije implanata su ograničene i moraju težiti što manjim vrednostima zbog ograničenog prostora u ljudskom organizmu, a vrednosti čvrstoće i žilavosti moraju biti dovoljno visoke.

Niske vrednosti Jangovog modula: Jangovi moduli biokompatibilnih metalnih materijala, koji se danas koriste u ortopedskoj hirurgiji, su pet do deset puta viši od Jangovog modula kosti, što je izuzetno nepovoljna karakteristika ovih materijala s obzirom da razlika modula elastičnosti metalnog materijala i kosti, koji se nalaze u kontaktu, uslovljava značajno opterećenje kosti i kao rezultat ima smanjenje gustine kostiju, /6/. Pomenute visoke vrednosti Jangovih modula implantnih materijala predstavljaju jedan od osnovnih razloga daljeg razvoja biokompatibilnih metalnih materijala, koji bi se mogli koristiti za izradu medicinskih implanata.

Biokompatibilnost: Implantni metalni materijali se moraju odlikovati izrazitom biokompatibilnošću, odnosno, izrazitim afinitetom ćelija prema površini implantnih metalnih materijala, a koja se razlikuje u zavisnosti od primene materijala u biomedicinskom inženjerstvu, /7/.

LJUDSKI ORGANIZAM KAO BIOLOŠKA SREDINA ZA BIOKOMPATIBILNE METALNE MATERIJALE

Pod normalnim uslovima, telesne tečnosti predstavljaju 0,9% sone rastvore, koji sadrže amino kiseline i proteine. Telesne tečnosti se sastoje od različitih tipova fluida, kao što su to tkivni fluidi, limfa i krv, ali sadrže i čvrste komponente, kao što su putujuće ćelije (leukociti i makrofage) i krvne čestice (limfociti, trombociti i eritrociti). U normalnim uslovima vrednost pH telesnih tečnosti je 7 (mada vrednost pH usled pojave zapalenjskih procesa izazvanih povredom ili hirurškim zahvatom može pasti na 4–5), a vrednost temperature i pritiska je 37°C i 1 atm (pri čemu unutrašnji parcijalni pritisak kiseonika predstavlja četvrtinu atmosferskog pritiska kiseonika), respektivno.

Opisana biološka sredina ljudskog organizma, je izuzetno korozivna za metalne materijale. Pre svega, niži parcijalni pritisak kiseonika u ljudskom organizmu nego na vazduhu ubrzava proces korozije biokompatibilnih metalnih materijala, jer se time smanjuje brzina oporavka pasivizirajućeg površinskog oksidnog filma nakon što se on ošteti ili ukloni sa površine materijala. U ljudskom organizmu koncentracija aktivnog kiseonika (kao što su O_2 i H_2O_2) može biti izuzetno visoka usled pojave zapalenjskog procesa, što vodi ka ubrzavanju procesa korozije metala prisutnih u ljudskom organizmu, /8, 9/. Pored toga čovek u toku dana, u proseku, načini nekoliko hiljada koraka sa učestalošću od 1 Hz. Iz tog razloga veštački kukovi i kolena, kičmeni fiksatori, pločice za fiksaciju kostiju i žice, koji su hirurškim putem ugrađeni u ljudski organizam, trpe promenljivo opterećenje, koje odgovara ciklusu hodanja, pa je nivo naprezanja implanta, npr. veštačkog kuka, nekoliko puta viši od uticaja težine samog ljudskog tela.

Durability: Materials placed inside the human body as implants should function as intended, without any damage, during the entire expected lifespan of the implant's recipient, from the first moment of implantation, implicating their exceptional high corrosion fatigue strength and corrosion fretting fatigue strength, as well as low release of fretting wear particles, /4,5/.

Strength and toughness: Implant dimensions must be kept low, since there is limited space in the human body, while strength and toughness of the implant material must be sufficiently high.

Low Young's *modulus:* Young's modules of biocompatible metallic materials used today in orthopaedic surgery are five to ten times higher than that of the bone, which is an extreme disadvantage of these materials, since the difference in elasticity modules of metallic materials and bones in mutual contact stipulates considerable tension in bones with a drop in bone density, /6/. These high values of the elasticity modules are one of the most significant reasons for further development of biocompatible metallic materials that can be used for manufacturing medical implants.

Biocompatibility: Metallic implant materials must have considerable biocompatible properties, *i.e.* they must have high cell affinity to the surface of metallic implant materials, and which differs with implant material application in the biomedical field, /7/.

HUMAN BODY AS A BIOLOGICAL ENVIRONMENT FOR BIOMETALLIC MATERIALS

Under normal conditions, human body fluids are 0.9% saline solutions containing amino acids and proteins. The human body fluids are composed of different fluid types, such as tissue fluids, lymph fluids and blood, but they also contain solid components, such as wandering cells (leukocytes and macrophages) and blood corpuscles (lymphocytes, thrombocytes and erythrocytes). Under normal conditions the human body fluids pH is 7 (although pH value may fall to 4–5 due to inflammation caused by surgery or injury), while temperature and pressure values are 37°C and 1 atm (where the internal partial pressure of oxygen is about one fourth of the atmospheric oxygen pressure), respectively.

Described biological environment of the human body is strongly corrosive for metallic materials. First of all, lower partial pressure of oxygen inside the human body than in air accelerates corrosion of biocompatible metallic materials, because the lower partial pressure of oxygen reduces the recovering speed of passive oxide films on the material surface, once it is broken or removed. The concentration of active oxygen in the human body, such as O_2 and H_2O_2, may become extremely high, due to the inflammation that can lead to accelerated corrosion of metallic materials in the human body, /8, 9/. In addition, human beings normally walk several thousand steps during one day at a rate of 1 Hz. Because of that surgically implanted artificial hip joints, knee joints, spinal fixations, bone plates and wires suffer from alternate stresses which correspond to the walking cycle, and so in the case of artificial hip joints, the stress level is several times higher than that produced by the body weight.

Kada su u pitanju pejsmejkeri, bitno je napomenuti da promenljivo opterećenje i naprezanje odgovara aktivnosti miokarda, dok kod dentalnih implanata promenljivo opterećenje odgovara ciklusu žvakanja.

Do pojave zamora materijala pri trenju dolazi usled napona koji se pri cikličnom trenju materijala dodaje osnovnom naponu. Kada dođe do zamora pri trenju, strano telo (metalni implant) je statički pritisnuto uz površinu objekta koji trpi ciklično naprezanje (kost). Trenje, koje se tada javlja, je rezultat relativnih pomeranja malih amplituda na kontaktnim površinama dve komponente usled koga se kompaktnost oksidnog sloja, formiranog na površini implanta, smanjuje, površinski sloj se kruni, što omogućava obrazovanje slobodne metalne površine, /10/. Na mestu kontakta se javlja prslina, koja se brzo širi, što izaziva lom metalnog materijala. Veštački kukovi, pločice za fiksaciju kostiju i žice, koje se koriste u ortopedskoj hirurgiji, često trpe opterećenje zbog pojave zamora pri trenju.

Unutar ljudskog organizma trenje metalnih materijala izaziva i pojavu habanja, koje dalje vodi ka neprekidnom oslobađanju metalnih jona, metalnih jedinjenja i produkata habanja (metalnih opiljaka). Oslobađanje svih navedenih metalnih produkata u živa tkiva, koja okružuju medicinski implant, mogu izazvati zatrovanost lokalnog tkiva ili obolelog organa, /11/, a dobar primer za to je pojava tkiva crne boje koje okružuje implant, što ukazuje na pojavu metalozisa (engl. *metallosis*) u kliničkoj ortopediji, /12, 13/.

Kada do pojave zamora materijala dođe istovremeno sa korozijom biokompatibilnog metalnog materijala, onda se govori o pojavi korozijskog zamora materijala, mada ova pojava može biti praćena i dodatnim trenjem koje se opisuje terminom frikciono-korozijski zamor materijala.

Prethodno navedeno pokazuje da ljudski organizam predstavlja izuzetno agresivnu sredinu za metalne materijale, kako u hemijskom pogledu, tako i u pogledu mehaničkih naprezanja, što utiče na smanjenje postojanosti biokompatibilnih implantnih metalnih materijala.

TITAN I LEGURE TITANA KAO IMPLANTNI METALNI MATERIJALI ZA PRIMENU U ORTOPEDIJI

Nerđajući čelici, kobalt-hrom legure i legure titana su osnovne grupe metalnih materijala koje se primenjuju u ortopediji, /2/. Već je rečeno da nijedna od ovih grupa nije posebno razvijena kao implantni materijal u biomedicinskom inženjerstvu, već su uvedene zbog izuzetne čvrstoće i otpornosti prema koroziji, ispoljene tokom primene u različitim granama industrije.

U poređenju sa nerđajućim čelicima i kobalt-hrom legurama, titan se odlikuje znatno boljom specifičnom čvrstoćom, ali i lošijim tribološkim karakteristikama. Takođe, vrednost modula elastičnosti titana je gotovo upola manja nego što je to slučaj kod nerđajućih čelika i kobalt-hrom legura, dok se na sobnoj temperaturi, zahvaljujući brzoj reakciji titana sa kiseonikom, na površini titana obrazuje veoma stabilan pasivizirajući zaštitni oksidni film, /14, 15/.

Titan se u prirodi javlja u dve kristalne modifikacije. Heksagonalno gusto pakovana struktura (c/a = 1,587) karakteristična je za titan do 882,5°C, i ta kristalna modifikacija titana se naziva α-titan.

In the case of a pacemaker electrode, one should notice that the alternating stresses and strains correspond to the myocardial activity, while alternating stresses correspond to the chewing cycle in the case of dental implants.

Material fretting fatigue occurrs due to cyclic friction stress superimposed to the basic fatigue stress. When fretting fatigue occurs, a foreign body (metallic implant) is statically pressed against the surface of the object to which the cyclic stress is applied (human bone). Fretting then occurs as a result of relative movements with a small amplitude between the contacting surfaces of the two components, resulting in oxide debris formation and metal surface fretting appearance, creating a fresh metallic surface, /10/. A crack initiates at the contact site that quickly propagates, resulting in metallic material fracture. Artificial hip joints, bone fixation plates and wires, used in orthopaedic surgery, often experienced the effect of fretting fatigue load.

Surface fretting of metallic materials inside the human body causes wear which leads to successive release of metallic ions, metallic compounds and fretting products (metallic debris). The release of these products into the tissues surrounding the medical implant may provoke toxicity on local tissue of the affected organ, /11/, and a good example for this phenomenon is the black-colouring of the tissue surrounding the implant in clinical orthopaedics, known as metallosis, /12, 13/.

When material fatigue occurs simultanuously with corrosion of biocompatible metallic material then we are talking about corrosion fatigue occurrence, although this phenomenon may be accompanied by additional fretting and than is described as material fretting corrosion fatigue.

According to the all above mentioned it can be concluded that the living body presents a chemically and mechanically harsh environment for metallic materials, and therefore it can influence and reduce the consistency of biocompatible implant metallic materials.

TITANIUM AND TITANIUM ALLOYS AS IMPLANT MATERIALS FOR APPLICATION IN ORTHOPEDICS

Commonly used metallic materials for application in orthopaedics are stainless steels, cobalt-chromium alloys and titanium alloys, /2/. As already mentioned, none of these alloys were developed specifically for biomedical engineering applications, but their exceptional strength and corrosion resistance, experienced in diverse industrial applications, has contributed to their use as implant materials.

Compared with stainless steels and cobalt-chromium alloys, titanium is superior in specific strength but inferior in tribological properties. In addition, the modulus of elasticity of titanium is about half, compared to that of stainless steels and cobalt-chromium alloys, while at room temperature, a very stable passive oxide film is formed at the free titanium surface due to rapid reaction with oxygen, /14, 15/.

In nature, titanium can be found in two allotropic modifications. Hexagonal close-packed structure (c/a = 1.587) is characteristic for titanium at temperatures below 882.5°C, and in that case we are talking about α-titanium (i.e. the alpha form).

Iznad 882,5°C, za titan je karakteristična zapreminski centrirana kubna struktura, koja se označava kao β-titan. Gustina α-titana iznosi 4,505 g/cm^3, dok je u slučaju β-titana vrednost gustine 4,320 g/cm^3, /16/.

Kao i kod bilo koje druge jednofazne legure, mikrostruktura čistog titana zavisi od toga da li je dobijena hladnom deformacijom, kao i od tipa žarenja, /1/. Mikrostruktura koja nastaje tokom hlađenja iz β oblasti (iznad 882,5°C) zavisi od samog procesa hlađenja, koji utiče na $\beta \rightarrow \alpha$ transformaciju, a otud i na veličinu i oblik dobijenih zrna α faze. Kako kinetika fazne transformacije $\beta \rightarrow \alpha$ jako utiče na svojstva titana i njegovih legura, to pri izboru termičke obrade treba voditi računa o efektu koji se postiže dodavanjem legirajućih elemenata. Svojstva titana i njegovih legura izuzetno su osetljiva na prisustvo čak i malih količina intersticijskih elemenata (vodonik, kiseonik, azot i ugljenik).

U literaturi se kategorizacija legura titana najčešće vrši prema fazama prisutnim u mikrostrukturi, pa se na osnovu tog parametra legure dele na α, $\alpha+\beta$ i β legure. U tabeli 1 uporedno su prikazana svojstva titana tehničke čistoće (CP) i nekih legura titana.

At temperatures above 882.5°C titanium has a body-centred cubic structure and in that case titanium is designated as β-titanium. The density of α-titanium is 4.505 g/cm^3, while the density of β-titanium is 4.320 g/cm^3, /16/.

Like that of any single-phase alloy, the microstructure of pure titanium depends upon whether it has been cold worked and on the type of annealing, /1/. Upon cooling from the β region (above 882.5°C) the forming structure will depend upon the cooling process, as this affects the $\beta \rightarrow \alpha$ transformation, and hence the final α grain size and shape. Since the kinetics of the $\beta \rightarrow \alpha$ phase transformation strongly influences the properties of titanium and its alloys, the effect of added elements should be considered in heat treatment choice. The properties of titanium and its alloys are sensitive to quite small amounts of interstitial elements (hydrogen, oxygen, nitrogen and carbon).

According to the references, titanium alloys are commonly divided into three categories, referring to the phases present in the microstructure, to α, $\alpha+\beta$ and β titanium alloys. The properties of commercially pure (CP) titanium and some titanium alloys are given in Table 1.

Tabela 1. Opšta svojstva titana tehničke čistoće i legura titana različitih tipova, /17/
Table 1. General properties of commercially pure titanium and titanium alloys of different types, /17/.

Svojstva materijala Material characteristics	Komercijalno čist Ti Commercially pure (CP) Ti	α legure α alloys	$\alpha+\beta$ legure ($\alpha+\beta$) alloys	β legure β alloys
Napon tečenja pri 20°C (MPa) Yield strength at 20°C (MPa)	300–700	700–850	850–1050	900–1000
Čvrstoća na povišenoj temperaturi High-temperature strength	niska (do 300°C) low (up to 300°C)	dobra (do 600°C) good (up to 600°C)	dobra (do 500°C) good (up to 500°C)	dobra (do 500°C) good (up to 500°C)
Otpornost na puzanje Creep resistance	niska (do 250°C) low (up to 250°C)	dobra (do 450°C) good (up to 450°C)	dobra (do 450°C) good (up to 450°C)	dobra (do 480°C) good (up to 480°C)
Toplotna stabilnost Heat stability	dobra good	dobra (do 500–600°C) good (up to 500–600°C)	dobra (300–500°C) good (300–500°C)	dobra (do 300°C) good (up to 300°C)
Sposobnost povećanja čvrstoće Strength increase capability	ne no	ne, u većini slučajeva no, in most cases	da yes	da, u većini slučajeva yes, in most cases
Deformabilnost na 20°C Deformability at 20°C	dobra do umerena, pri 300°C dobra good or moderate, good at 300°C	slaba, pri 600–700°C dobra low, good at 600–700°C	slaba, pri 500–650°C dobra low, good at 500–650°C	umerena, pri 500°C dobra moderate, good at 500°C
Zavarljivost Weldability	dobra good	dobra good	od dobre do loše from good to poor	dobra good

α legure titana

Osnovna faza legura titana, α, prisutna je u mikrostrukturi na temperaturama ispod 800°C. S obzirom da preovladava α čvrsti rastvor titana (najmanje 95% mas.), svojstva ovih legura se ne mogu značajno menjati termičkom obradom, /1/. Ojačavanje α legura titana se postiže hladnom deformacijom, kombinacijom hladne deformacije i žarenja, čime se kontroliše veličina α zrna, kao i rastvarajućim ojačavanjem. Najveći uticaj rastvarajućeg ojačavanja kod α legura titana imaju aluminijum, silicijum, vanadijum, cirkonijum, niobijum i kalaj, velike ili srednje rastvorljivost u titanu, a njihova upotreba je i ekonomična.

Međutim, bitno je istaći da od svih navedenih elemenata jedino aluminijum, kalaj i cirkonijum stabilizuju α fazu. Zbog toga se pri razmatranju efekata ojačavanja čvrstim rastvorom α legura titana uzimaju u obzir samo ova tri elementa.

α titanium alloys

The common titanium alloys phase, α, is present in microstructure at low temperatures, below 800°C. Since α solid solution is prevailing (at least 95% mass), the properties of this alloys cannot be significantly altered by heat treatment, /1/. Strengthening of α titanium alloys can be achieved by cold working, combining cold working and annealing in order to control the α grain size, or by solid solution. Most effect in solution strnghening for α titanium alloys exhibited aluminium, silicon, vanadium, zirconium, niobium and tin, with high or medium solubility in titanium and all may be economical to use.

However, it must be noted that among the upper mentioned elements, only aluminium, tin and zirconium stabilize the α phase. So, when considering effects of solid solution strengthening of α titanium alloys, only these three elements are considered.

Tako se dodavanjem aluminijuma i kalaja postiže znatno ojačavanje titana, dok se čvrstoća samo neznatno povećava dodatkom cirkonijuma. Otuda se ovaj element i ne koristi u te svrhe. S druge strane, dodatak aluminijuma i kalaja može dovesti, pored već pomenutih efekata, i do povećanja krtosti legure.

U eksploataciji legura titana, posebna pažnja se mora obratiti na naponsku koroziju i na prsline naponske korozije. Korozivna sredina, npr. slana voda ili vlažan vazduh, može smanjiti visok nivo čvrstoće materijala, postignuta termičkom obradom i materijal postaje podložan stvaranju i širenju prslina. Sadržaj aluminijuma u leguri značajno utiče na pojavu i razvoj naponske korozije, posebno kod termički obrađenih legura titana sa manje od 7% mas. Al. Dobar primer je žarenje na 1200°C u β oblasti, a zatim hlađenje u vodi uz obrazovanje α martenzita, kada ni brzim hlađenjem nije moguće izbeći stvaranje određene količine α_2–Ti_3Al faze. Obrazovanje α_2–Ti_3Al faze smanjuje mogućnost stvaranja prslina usled dejstva naponske korozije u slanoj vodi, a donekle i u vazduhu, ali se stvaranjem dvofazne $\alpha + \alpha_2$–Ti_3Al mikrostrukture, dejstvo naponske korozije pojačava.

Sledeća bitna karakteristika visokočvrstih legura, koja se razmotriti pri njihovoj eksploataciji, je njihova osetljivost na zareze, odnosno osetljivost na koncentraciju napona. Osetljivost na koncentraciju napona se definiše kao mera sposobnosti materijala da se u područjima velikih napona lokalno plastično deformiše, umesto da dođe do pojave prsline ili loma. Osetljivost materijala na zareze se određuje ispitivanjem zatezanjem epruvete, na kojoj je prethodno napravljen zarez radi koncentracije napona, i upoređivanjem dobijene vrednosti sa zateznom čvrstoćom, vrednošću koja je dobijena ispitivanjem zatezanjem glatke epruvete. Kod Ti-Al legura, čak i za mali sadržaj Al u leguri, osetljivost na zarez je izražena, a taloženje krte α_2–Ti_3Al faze, se pokazalo kao osnovni razlog tome. Da bi se povećala čvrstoća legure, a u isto vreme održao određen nivo žilavosti, koriste se trojne legure. Najčešće korišćena α legura titana sadrži 5% mas. Al i 2,5% mas. Sn.

Prisustvo ugljenika, kiseonika i azota u intersticijskim položajima dovodi do promene mehaničkih svojstva α legura na sličan način kao i kod čistog titana, /18/. Ovi elementi povećavaju čvrstoću, a smanjuju duktilnost α legure.

β legure titana

U grupu β legura titana svrstavaju se legure kod kojih u mikrostrukturi preovladava čvrst rastvor na osnovi β modifikacije titana. Osnovni legirajući elementi β legura titana su vanadijum, molibden, volfram, hrom i niobijum, koji pripadaju grupi takozvanih β stabilizatora. U sastav ovih legura skoro uvek ulazi i aluminijum koji utiče na značajno povećanje čvrstoće. Zahvaljujući kubnoj rešetki, karakterističnoj za β fazu, lakše se podvrgavaju hladnoj deformaciji od α i $\alpha+\beta$ legura. Termičkom obradom, tj. procesom kaljenja i starenja, čvrstoća β legura se može povećati u velikoj meri, a jedna od osnovnih karakteristika ovih legura je svakako i dobra zavarljivost. Iako se do 400°C odlikuju visokom čvrstoćom, otpornost na puzanje je manja nego kod α legura titana.

Apparently, the addition of aluminium and tin affects significant titanium strengthening, while addition of zirconium only slightly improve it. Thus, zirconium is not used for strengthening of α titanium alloys. However, addition of aluminium and tin can not only improve alloy strength, but also enhance embrittlement.

An important consideration in using titanium alloys is stress-assisted corrosion and stress corrosion cracking. A corrosive environment, e.g. salt water and moist air, can lower the material strength achieved by heat treatment and make it susceptible to crack formation and propagation. The effect of aluminium content on the alloy stress corrosion behaviour can be significant, particularly in the case of heat treated alloy with the aluminium content below 7% mass. Good example is annealing at 1200°C in the β region, followed by water quenching and α martensite formation, during which even rapid cooling could not suppress the formation of some α_2–Ti_3Al. The formation of α_2–Ti_3Al lowers the fracture stress somewhat in air and especially in seawater, however the stress corrosion is increased with formation of two-phase $\alpha + \alpha_2$–Ti_3Al microstructure.

Another important characteristic of high-strength alloys that must be considered in exploitation is notch sensitivity, that is sensitivity to stress concentration. Sensitivity to stress concentration can be defined as a measure of the material's ability to plastically deform locally at regions of high stress, instead crack initiation occurrence and fracture. Material notch sensitivity is determined by conducting a tensile test with specimen pre-notched for stress concentration, and comparing the obtained value with the tensile strength, the value obtained by tensile tsting of smooth specimen. The notch sensitivity of Ti-Al alloys, even with low aluminium contents, is highly expressed, and precipitation of the brittle α_2–Ti_3Al phase is proved to be the main reason for that. In order to increase the strength and yet retain reasonable toughness, ternary alloys may be used. The most commonly used α titanium alloy contains 5% mass Al and 2.5% mass Sn.

Presence of interstitial elements, such as carbon, oxygen and nitrogen, affect α titanium alloys in a way similar to the way they affect pure titanium, /18/. These elements increase strength and decreases ductility of α titanium alloy.

β titanium alloys

β titanium solid solution prevails in the microstructure of β titanium alloys. Basic alloying elements in β titanium alloys are vanadium, molybdenum, tungsten, chromium and niobium. These elements are called β stabilizers. Aluminium, as an element that increases alloy strength, is almost always an additional element in the β titanium alloy composition. Thanks to the characteristic cubic structure of the β phase, β titanium alloys are easily cold worked, especially when compared to α and $\alpha+\beta$ titanium alloys. Strength of β alloys can be increased by heat treatment, such as quenching and ageing. Good weldability is one of the main characteristics of this alloy group. Even though β alloys possess high strength below 400°C, their creep resistance is lower compared to α titanium alloys.

Zbog velike simetrije i velikog broja ravni klizanja koju omogućuje njihova struktura, ove legure se odlikuju izuzetnom mogućnošću plastične deformacije. Starenjem je pak omogućeno taloženje α faze u β mikrostrukturi, čime se obezbeđuje odlična čvrstoća.

$\alpha + \beta$ legure titana

Dvofazne legure ovog tipa dobijaju se legiranjem titana elementima koji obrazuju α i β čvrste rastvore. Termičkom obradom $\alpha + \beta$ legura titana moguće je značajno povećati njihovu čvrstoću uz relativno malo smanjenje plastičnosti. Zavarljivost $\alpha + \beta$ legura je ograničena.

Pored aluminijuma, $\alpha + \beta$ legure titana sadrže dodatne legirajuće elemente koji stabilizuju β fazu. To su elementi sa zapreminski centriranom kubnom rešetkom, kao što su molibden i vanadijum, koji ujedno predstavljaju i najvažnije legirajuće elemente titanovih $\alpha + \beta$ legura.

Kada je reč o termičkoj obradi legura titana, od velikog značaja je β tranzus temperatura, koja predstavlja temperaturu faznog preobražaja $\beta \rightarrow \alpha + \beta$ i iznad koje je stabilna samo β faza. Naime, pri sporom hlađenju $\alpha + \beta$ legura sa niskim sadržajem legirajućih elemenata u β oblasti, doći će do obrazovanja α faze. Međutim, kada je u leguri prisutna dovoljno velika količina legirajućih elemenata, obrazovaće se dvofazna $\alpha + \beta$ mikrostruktura sa α fazom bogatom titanom i β fazom bogatom legirajućim elementom. Udeo β faze zavisi od stepena legiranja i povećava se sa povećanjem sadržaja legirajućeg elementa u leguri.

Prednosti primene titana i legura titana u medicinskom inženjerstvu

Komercijalno čist titan, koji se popularno obeležava kao CP titan, odlikuje se jednofaznom α mikrostrukturom. CP titan može sadržati izuzetno nisku količinu železa, azota i kiseonika, dok je ukupan sadržaj ostalih elemenata obavezno niži od 0,7%. Zbog neznatnih ali strogo definisanih razlika u sastavu, CP titan se proizvodi u četiri osnovna sastava, koji se obeležavaju brojevima od 1 do 4. Sa porastom broja raste i vrednost zatezne čvrstoće kojom se odlikuju ti sastavi. U odnosu na legure titana, čist titan se karakteriše povećanom otpornošću prema koroziji, dok se α legure titana odlikuju boljom otpornošću prema povišenim temperaturama i boljom zavarljivošću od β legura, pri čemu im je čvrstoća i mogućnost oblikovanja niža.

Dugogodišnjim istraživanjima uspešno su razvijene dvofazne $\alpha + \beta$ legure, sa dispergovanom β fazom u α fazi, sa odličnim karakteristikama svojstvenim i jednoj i drugoj fazi. Dvofazna $\alpha + \beta$ legura koja je našla široku primenu u medicinskom inženjerstvu je legura Ti-6Al-4V. Mikrostruktura, a samim tim i svojstva ove legure, u velikoj meri zavise od termomehaničkog tretmana kojima je izložena tokom izrade, pa se zatezna čvrstoća može kretati u rasponu od ~ 930 MPa za liveno stanje, /11/, i do ~ 1200 MPa za rastvarajuće žareno i stareno stanje, /19/. Legura, u čijem sastavu je sadržaj nečistoća snižen kako bi se žilavost na niskim temperaturama i otpornost prema širenju prsline poboljšale, naziva se legurom sa izuzetno malo intersticijala (ELI), odnosno, ELI Ti-6Al-4V legura.

In addition, β titanium alloys show excellent plastic deformability because of their high symmetry and many slip planes. Aging treatment even enables α phase precipitation in all-β structure which in turn enables excellent strength of these alloys.

$\alpha + \beta$ titanium alloys

Two-phase $\alpha + \beta$ titanium alloys are obtained by alloying titanium with α and β solid solution forming elements. Significant improvement of $\alpha + \beta$ titanium alloy strength, with relative minor drop in plasticity, can be achieved by heat treatment. Weldability of these alloys is limited.

Except aluminium, as additional alloying elements, $\alpha + \beta$ titanium alloys also contain elements designated as β stabilizers. These elements, such as molybdenum and vanadium, have body-centred cubic structure and represent the most important alloying elements of $\alpha + \beta$ titanium alloys.

A term frequently used in discussing heat treatment of titanium alloys is the β transus temperature, the temperature of $\beta \rightarrow \alpha + \beta$ phase transformation, above which only β phase is stable. Namely, upon slow cooling of $\alpha + \beta$ alloys with low content of alloying elements in the β region, formation of α phase will occur. However, with sufficient content of alloying elements, the two-phase $\alpha + \beta$ structure with α phase rich in titanium and β phase rich in alloying elements, will be present. The amount of β phase is strongly dependent on the overall content of alloying elements and it increases with the overall increase of alloying elements.

Advantages of titanium and titanium alloys in medical applications

Commercially pure (CP) titanium has an all-α single phase microstructure. CP titanium can contain very small amounts of iron, nitrogen and oxygen, while the total amount of other elements must be lower than 0.7%. Because of slight, but strictly defined differences in composition, there are four CP titanium grades marked with numbers from 1 to 4. Larger grade numbers designating CP titanium composition, indicate higher tensile strength values. Compared to titanium alloys, pure titanium is characterised by superior corrosion resistance, while α titanium alloys are superior in heat resistance and weldability, but inferior in strength and workability, compared to β titanium alloys.

Long term researches resulted in the development of two-phase $\alpha + \beta$ alloys with a dispersed β phase in the α phase, contributing to excellent characteristics of each of the two phases. A typical and widely used in medical engineering two-phase $\alpha + \beta$ alloy is Ti-6Al-4V. The microstructure and thus the properties of the this alloy strongly depend on the thermomechanical and heat treatments in its production, and so the ultimate strength values range from ~ 930 MPa for the annealed alloy, /11/, to ~ 1200 MPa for the solution-treated and aged alloy, /19/. The alloy whose impurities are reduced in order to improve toughness at low temperature, as well as crack propagation resistance, is called ELI (extra low interstitial), or ELI Ti-6Al-4V alloy.

Titan i legure titana su izuzetno zanimljive za primenu u medicini zbog njihove izuzetne biokompatibilnosti, specifične čvrstoće, niskih Jangovih modula i dobre otpornosti prema koroziji. Njihova izuzetna biokompatibilnost potvrđena je ispitivanjima na životinjama, kao i dugogodišnjim kliničkim ispitivanjima sa pacijentima. Takođe, oksidisane površine titana i legura titana se izuzetno ponašaju kada se nalaze u kontaktu sa kostima, postajući osteo-integrisane u vrlo kratkom roku sa neznatnim fibroznim slojem između same kosti i implanta.

Komercijalno čist titan se pre svega koristi u stomatologiji za izradu dentalnih implanata, mada se koristi i u ortopediji u vidu žičanih mrežica, koje služe kao porozne prevlake sinterovane na površini veštačkih zglobova izrađenih od legura titana.

Relativno niske vrednosti modula elastičnosti, karakteristične za legure titana, utiču na smanjenje krutosti konstruisanih implanata bez potrebe za menjanjem njihovog oblika. Dobar primer za to su vrednosti aksijalne, savojne i torzione krutosti pločice za fiksaciju kosti izrađene od legure titana, koje su upola niže nego kod pločica za fiksaciju kosti istih dimenzija i oblika, ali izrađenih od nerđajućeg čelika ili legure kobalta. Iz tog razloga bi u slučaju primene pločica za fiksaciju, koje su kruto pričvršćene za ljudsku kost, naprezanje prisutno u kosti bilo znatno manje pri primeni legura titana. Ova razmatranja mehaničkih karakteristika legura titana su potvrdila da su ove legure idealne za proizvodnju uređaja za fiksaciju kičmenih pršljenova i slomljenih kostiju, uključujući izradu pločica, ugala i vijaka, ali i kao osnova za izradu veštačkih zglobova i zglobnih implanata.

Relativno niska tvrdoća legura titana, međutim, utiče na njihovu slabu otpornost prema habanju, pa se ove legure bez prethodne dodatne površinske obrade, kao što je jonska implementacija, ne mogu koristiti za izradu zglobnih površina. Bez obzira na dugogodišnja klinička ispitivanja, koja su pokazala odličnu biokompatibilnost legura titana, još uvek se javlja bojazan od oslobađanja toksičnih elemenata, kao što je vanadijum, zbog čega su u biomedicinsko inženjerstvo počele da se uvode nove legure titana u čijem sastavu je vanadijum zamenjen inertnijim elementima, kao što je niobijum.

U tabeli 2 prikazani su ASTM standardi titana i legura titana za primenu u medicini i hirurgiji, /20/, a u tab. 3. je dat spisak primenljivih materijala.

Titanium and its alloys are of particular interest for biomedical applications because of their outstanding biocompatibility, specific strength, low Young's modulus and high corrosion resistance. Their superior biocompatibility was confirmed in long-term clinical experiments on animals and humans. Furthermore, the oxide surfaces of titanium and titanium alloys are well tolerated in contact with bone, becoming osteo-integrated in a very short period, with little evidence of any fibrous layer between bone and implant.

Commercially pure titanium is more extensively used in dentistry as a dental implant material. However, it is also used in orthopaedics in the form of wire mesh for porous coatings that are sintered onto titanium alloy joint replacement components.

Relatively low elasticity modulus values, typical for titanium alloys makes them ideal candidates for lowering the implant structural stiffness without changing their shape. A good example are for that are the values of axial, bending and torsional stiffness of a bone plate, produced from titanium alloy, which are one half of stiffness than of a bone plate of the same size and shape, produced from stainless steel or cobalt alloy. Thus, the severity of stress shielding when the plate is rigidly attached to the bone would be significantly lower in the case of the titanium alloy plate. The considerations of mechanical characteristics of titanium alloys aprooved that these alloys are ideal for the application in manufacturing of fracture and spinal fixation devices, including plates, nails and screws, as well as in stems for total artificial joint replacements and joint implants.

However, the relatively low hardness of titanium alloys influences poor wear resistance, suggesting that titanium alloys must undergo additional surface processing, e.g. ion implementation, before their use in articulating joint surface manufacture. Despite of long-term clinical evidence of the excellent biocompatibility of titanium alloy, concerns about the release of cytotoxic elements, such as vanadium which could cause local and systematic problems, have led to the limited introduction of other titanium alloys in which vanadium has been replaced by more inert elements such as niobium.

ASTM standards of titanium and titanium alloys for medical and surgical use are shown in Table 2, /20/, and in Table 3 a list of applicable materials is presented.

Tabela 2. Standardi koji se odnose na titan i legure titana za izradi medicinskih implanata.
Table 2. Standards related to titanium and titanium alloys for surgical implants.

Specifikacija Specification	Nominalni sastav Nominal composition
F67-95	nelegirani titan / unalloyed titanium
F136-98	kovana Ti-6Al-4V ELI legura / wrought Ti-6Al-4V ELI alloy
F620-97	Ti-6Al-4V ELI legura / Ti-6Al-4V ELI alloy
F1108-97a	livena Ti-6Al-4V legura / Ti-6Al-4V alloy castings
F1295-97a	kovana Ti-6Al-7Nb legura / wrought Ti-6Al-7Nb alloy
F1472-96	kovana Ti-6Al-4V legura / wrought Ti-6Al-4V alloy
F1713-96	kovana Ti-13Nb-13Zr legura / wrought Ti-13Nb-13Zr alloy
F1813-97	kovana Ti-12Mo-6Zr-2Fe legura / wrought Ti-12Mo-6Zr-2Fe alloy

Tabela 3. Metalni materijali za primenu u medicini i stomatologiji, /2/.
Table 3. Metallic materials used for medical and dental devices, /2/.

Specijalističke oblasti Clinical division	Medicinski uređaj Medical device	Metalni materijal Metallic material
Ortopedska hirurgija Orthopaedic surgery	Fiksatori kičme / Spine fixation	316L*, Ti, Ti-6Al-4V
	Fiksatori kosti / Bone fixation	316L, Ti, Ti-6Al-4V
	Veštački zglobovi / Artificial joints	Co-Cr, Ti-6Al-4V
	Razmicači kičme / Spinal spacers	316L, Ti-6Al-4V
Kardiovaskularna medicina i hirurgija Cardiovascular medicine and surgery	Implantno veštačko srce / Implant-type artificial heart	Ti
	Pejsmejker (kućište) / Pacemaker (case)	Ti, Ti-6Al-4V
	Elektronske žice / Electric wires	Ni-Cr
	Elektroda / Electrode	Ti, Pt-Ir
	Terminal / Terminal	Ti, 316L l, Pt
	Veštački zalizak / Artificial valve	Ti-6Al-4V
	Stent / Stent	316L, Ni-Ti, Ta
	Žica vođica / Guide wire	316L, Ni-Ti, Co-Cr, Pt
	Embolizaciona žica / Embolization wire	Ti-6Al-4V, 630 nerđajući čelik 630 stainless steel, Co-Cr, Pt
	Okvir / Clip	316L
Otorinolaringologija Otorhinolaryngology	Veštačko unutrašnje uho (elektroda) Artificial inner ear (electrode)	Pt
	Veštačka bubna opna / Artificial eardrum	316L
Stomatologija Dentistry	Umetak, krunica, most, spona, dentinska osnova Inlay, crown, bridge, clasp, denture base	Au-Cu-Ag, Au-Cu-Ag-Pt-Pd, Ag-Pd-Cu-Au, Ti, Co-Cr
	Porcelanski spoj sa metalom / Porcelain fused to metal	Au-Pt-Pd
	Dentalni implant / Dental implant	Ti, Ti-6Al-4V
	Ortodontska žica / Orthodontic wire	316L, Co-Cr, Ni-Ti, Ti-6Al-4V
	Magnetsko pričvršćenje Magnetic attachment	Sm-Co, Nd-Fe-B, Pt-Fe-B, Pt-Fe-Nb, 444 nerđajući čelik, 444, 316L
Opšta hirurgija General surgery	Igla za špric / Needle of syringe	304 nerđajući čelik / 304 stainless steel, 316L
	Skalpel / Scalpel	420J1 nerđajući čelik / 420J1 stainless steel
	Katetar Catheter	Ni-Ti, 304 nerđajući čelik, 304 stainless steel, 316L, Co-Cr, Au, Pt-In
	Spajalica / Staple	630 nerđajući čelik / 630 stainless steel

* 316L je nerđajući čelik (316L is stainless steel)

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