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BIOCOMPATIBLE Zr-Ti-Nb ALLOY FOR MEDICAL IMPLANTS: CHARACTERIZATION OF PROPERTIES AND COMPARISON WITH Ti-6Al-4V

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Study presents an investigation of a novel biocompatible Zr-Ti-Nb alloy developed for medical implant applications. The study encompasses analysis of the alloy's chemical composition, structural, physical, and mechanical properties, alongside a comparative evaluation against the conventional titanium alloy Ti-6Al-4V. The Zr-Ti-Nb alloy demonstrates a low elastic modulus (26.4 GPa), closely matching that of cortical bone, superior plasticity, satisfactory corrosion resistance, and absence of toxic elements, making it a promising candidate for implantology.

Over the past several decades, significant attention within the scientific community has been directed towards the development of biocompatible implant materials that combine high strength, corrosion resistance, and minimal toxicity. Titanium alloys, particularly commercially pure titanium and Ti-6Al-4V, have been predominantly employed due to their favorable mechanical properties and biocompatibility, gaining extensive application in orthopedics, dentistry, and craniofacial surgery. the Ti-6Al-4V alloy, remain the most widely used implant materials. However, these alloys exhibit several drawbacks: their elastic modulus (105-115 GPa) significantly exceeds that of cortical bone (15-30 GPa), and they contain potentially toxic elements (Al, V) that may leach into the biological environment. Consequently, the search for alternative alloys with enhanced properties continues [1]. One promising avenue involves Zr-Ti-Nb system alloys, which combine biocompatibility, a reduced elastic modulus, and absence of toxic constituents. Previous studies proposed a novel alloy with a chemical composition of 59.57 wt. % Zr, 19.02 wt. % Ti, 21.41 wt. % Nb, and an elastic modulus of 27.27 GPa. The current research aims to further evaluate the properties of this alloy and compare them with those of Ti-6Al-4V, to substantiate its potential as a state-of-the-art implant material [2].

The experimental Zr-Ti-Nb alloy samples were fabricated using the technology described in previous studies. For comparative purposes, commercially available Grade 5 titanium alloy Ti-6Al-4V was procured from the Zaporizhzhia Titanium & Magnesium Combine (Ukraine).

The chemical compositions of the alloys were determined by X-ray fluorescence analysis employing the EXPERT 4L express analyzer. Phase composition and structural parameters were evaluated via X-ray diffraction using a DRON-3 diffractometer in Bragg-Brentano geometry with Co-Kα radiation.

Morphology and elemental distribution within the samples were examined by scanning electron microscopy (SEM) using a Tescan Mira 3 MLU microscope equipped with an Oxford X-Max 80 mm² energy-dispersive spectrometer, operated at an accelerating voltage of 15 kV.

Surface wettability measurements were conducted by optical microscopy through contact angle determination on samples both with native oxide layers and after mechanical surface treatment using 200-grit sandpaper.

Corrosion resistance was assessed by recording polarization curves in a 0.9 % NaCl solution using a three-electrode electrochemical cell, a PI-50-1 potentiostat, and PR-8 software. A silver/silver chloride (Ag/AgCl) electrode served as the reference electrode.

Density measurements were performed by two methods: direct volume measurement of cylindrical specimens and water displacement. Reflectivity was determined using an FB-2 photoflash meter relative to a silver mirror standard.

Mechanical properties – including ultimate tensile strength, yield strength, elastic modulus, elongation, and reduction in area – were obtained via tensile testing on a P-5 universal testing machine following the Ukrainian state standard DSTU ISO 6892-1:2019. Specimens were prepared in a “dog-bone” shape. Hardness was measured using a Vickers Hardness Tester (432SVD) and a PMT-3 microhardness tester.

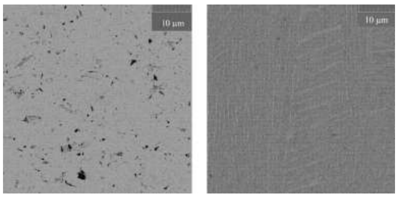
To ensure statistical reliability, three samples were tested for each method, with significance levels established at 90 confidence ($p < 0.1$).

As shown in Table 1, the chemical composition analysis revealed that the Zr-Ti-Nb alloy consists primarily of the main components with minor iron impurities, whereas the Ti-Al-V alloy contains additional impurities exceeding 1 %. Phase analysis showed the predominance of zirconium and niobium phases in the Zr-Ti-Nb alloy, with minor amounts of Ti and $NbTi_4$ phases (up to 2 %) and no significant other phases. In contrast, the Ti-Al-V alloy primarily consists of a titanium phase with the presence of Al_5Ti_3, $AlTi_2$, and an unidentified phase (~2 %), likely containing vanadium.

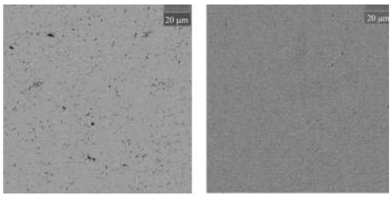
Table 1 – Chemical composition of alloys

Alloy	Element content, wt.%									
	Ti	Zr	Nb	Fe	Al	V	Cr	Ni	Si	S
Ti-Al-V	88.5	-	-	0.5	6.43	3.94	0.25	0.19	0.1	0.05
Zr-Ti-Nb	17.39	64.28	18.1	0.23	-	-	-	-	-	-

SEM images (Fig. 1) of the Zr-Ti-Nb alloy surface demonstrated a uniform distribution of elements with three distinct zones evenly distributed across the surface, which does not adversely affect the mechanical properties. Conversely, two unevenly distributed zones were identified in the Ti-Al-V alloy, which may degrade its mechanical characteristics.



a b



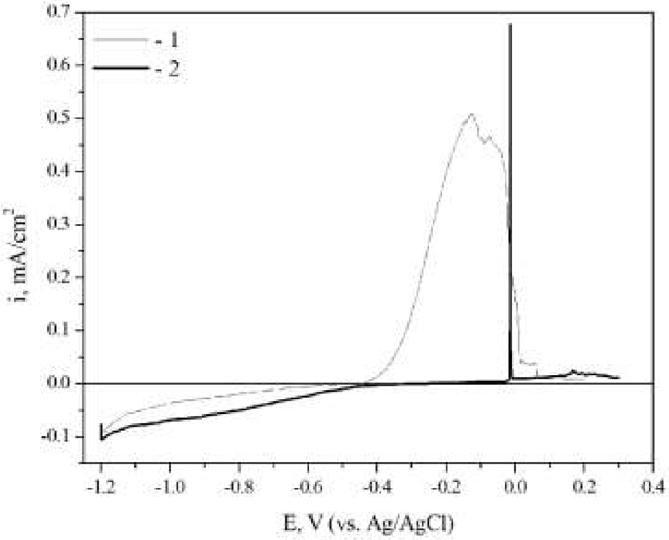
c d

a, c – Zr-Ti-Nb; and b, d – Ti-Al-V

Fig. 1. SEM images of the surface of alloy samples obtained by scanning electron microscopy at different magnification

Alloys covered with an oxide layer exhibited significantly lower contact angles (Zr-Ti-Nb ~45°, Ti-Al-V ~64°), indicating higher hydrophilicity of the Zr-Ti-Nb alloy and a potential enhancement of osseointegration. Mechanical surface treatment increased the contact angle to approximately 102-104°, rendering the surfaces hydrophobic.

Polarization curves (Fig. 2) revealed three anodic peaks for the Zr-Ti-Nb alloy corresponding to the oxidation of Zr, Nb, and Ti, while only a single oxidation peak of Ti was observed for the Ti-Al-V alloy. The Ti-Al-V alloy exhibited a higher corrosion potential (+0.288 V) compared to the Zr-Ti-Nb alloy (–0.45 V); however, anodic oxidation can improve the corrosion resistance of the Zr-Ti-Nb alloy.



1 – Zr-Ti-Nb; 2 – Ti-Al-V

Fig. 2. Polarization curves of the alloys under study. The curves were recorded in a solution of 0.9 wt.% NaCl. The potential scan rate was 0.001 V/s

The density of the Zr-Ti-Nb alloy is 34 % higher than that of Ti-Al-V, while electrical conductivity and reflectivity differ insignificantly.

Tensile testing (Fig. 3) of Zr-Ti-Nb samples revealed an elastic modulus of 26.44 GPa, closely matching that of cortical bone (15-30 GPa), which is advantageous compared to the Ti-Al-V alloy with an elastic modulus of 105-115 GPa. The Zr-Ti-Nb alloy exhibits high plasticity and deformability, as evidenced by fractographic analysis showing a characteristic ductile “cup-and-cone” fracture surface.

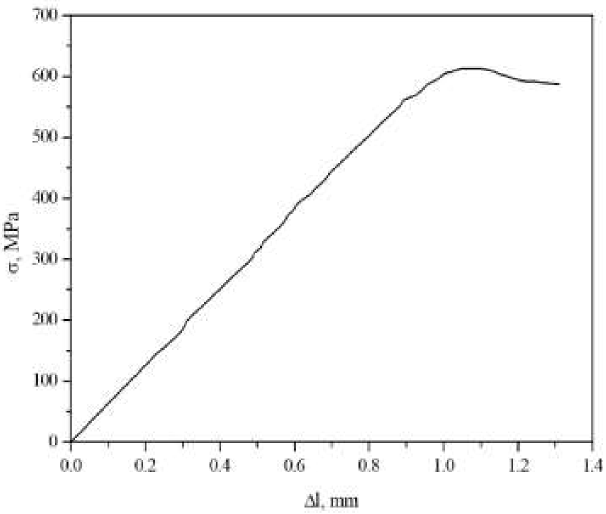


Fig. 3. Experimental tensile diagrams of the Zr-Ti-Nb alloy

Although the hardness of the Ti-Al-V alloy is 30-36 % higher, it exhibits lower plasticity and a propensity for crack formation due to the uneven distribution of zones across its surface.

These findings support the recommendation of the Zr-Ti-Nb alloy for further investigation and potential implementation in the production of medical implants.

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РОЗРОБКА РЕКОМЕНДАЦІЙ ЩОДО РЕЖИМІВ ДРУКУ ЗАДЛЯ МІНІМІЗАЦІЇ ШОРСТКОСТІ ПОВЕРХНІ ДЕТАЛЕЙ, ВИГОТОВЛЕНИХ МЕТОДОМ LPBF

Виробництва деталей способом Laser Powder Bed Fusion (LPBF) останні роки набуває широкого впровадження. Це пов'язано з можливістю швидкого прототипування деталей з досягненням високої щільності високодисперсної зеренної структури, що в свою чергу сприяє формуванню високих механічних властивостей. Але слід зазначити, як і всі технології виробництва деталей, дана технологія має ряд актуальних матеріалознавчих питань, що потребують уваги.