



Article

Influence of Chemical Composition on the Physical–Mechanical Properties of Some Experimental Titanium Alloys for Dental Implants

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Abstract

Background/Objectives: The main objective of optimizing the composition of dental implants is to improve tissue compatibility for enhanced biological/biochemical performance. In this context, research on the development of new titanium alloys in dental implantology considers the careful selection of alloying elements, both in terms of biocompatibility (their lack of toxicity) and their potential to improve the metallurgical processing capacity (thermal and/or thermomechanical), which through controlled microstructural changes lead to the optimal combination of properties for functionality and durability of the implant. The purpose of the research is to study the influence of alloying elements on the phase composition and physical–mechanical properties of experimental titanium alloys. **Methods:** Four alloys with original chemical compositions were developed, coded in the experiments as follows: Ti1, Ti2, Ti3, Ti4. The characterization of the alloys was carried out by detailed analysis of the chemical composition, phase structure and by testing the physico-mechanical properties (HV hardness, tensile strength, yield strength, elongation, modulus of elasticity), by standardized modern methods. Characterization methods, such as optical microscopy, SEM, EDS and XRD were performed,

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followed by tensile tests based on ASTM EB/EBM-22 and EN ISO 6892-1-2009 standards. **Results:** The research results provide information regarding the relationship between the composition and the physico-mechanical properties (R_m , R_p , HV, A, G, E) of the experimental alloys (Ti1–Ti4). Depending on the value level of the properties, these have been highlighted: compositions in which the alloy can be indicated for conditions of intense stress (Ti3), compositions that describe highly ductile alloys, easy to process and adapt to clinical requirements (Ti4), but also alloys compositions characterized by a balanced combination of strength, plasticity/ductility (Ti1, Ti2). **Conclusions:** Research for the development of new titanium alloys through the optimization of chemical composition has taken into account the requirements regarding the biological/biomechanical compatibility of biomaterials. Analyzed in comparison with Cp-Ti grade 4 and Ti6Al4V, the experimental alloys (Ti1–Ti4) can be characterized as follows: The mechanical strength properties (R_m and R_p) are higher than those of pure commercial titanium (Cp-Ti grade 4) for all compositions Ti1–Ti4, but slightly lower than those of alloy Ti6Al4V. The plasticity–ductility properties have values comparable to those of Cp-Ti grade 4 (Ti4 and Ti2 compositions) and Ti6Al4V (Ti1 composition), with one exception, the Ti3 alloy. All four experimental alloys have a lower modulus of elasticity than Cp-Ti grade 4 (102–104 GPa) and Ti6Al4V (113 GPa), commonly used in dental implants. An in-depth analysis, which will also consider information on corrosion behavior and cellular testing, may support the selection of some of the four experimental alloys studied. The research aims to continue the progress to a higher level of testing, through the realization of dental implants (e.g., fatigue, wear, osseointegration capacity, etc.).

Keywords: dental implants; new experimental Ti-alloys; microstructure; mechanical properties

1. Introduction

Metals and alloys are widely used as biomedical materials [1–4]. Their selection for the realization of implantable medical devices is based on the existence of a balance between the mechanical properties of resistance and their biological accounting [5–9]. The achievement of osseointegration and the maintenance of the tissue bio integration of the implant depend decisively on the intrinsic biocompatibility of the material and both on the extrinsic or functional biocompatibility, expressed by its biomechanical properties [10–15].

The metallic biomaterials intended for the manufacture of the dental implant must meet a set of basic properties, namely, high mechanical strength to withstand chewing forces, optimal hardness to prevent wear, sufficient ductility to allow adaptation to the biomechanical conditions of the bone, a low modulus of elasticity to avoid the shielding effect of bone stress and to ensure good osseointegration [16,17]. From this point of view, compared to other metal materials, titanium and titanium alloys are still considered to be the most suitable [18–29].

In dental implantology, pure commercial titanium (Cp-Ti) is used in four degrees of purity according to the oxygen content at processing [30,31]. Cp-Ti grade 1 has the lowest oxygen content, good corrosion resistance and good machinability, but the overall mechanical strength is low. Cp-Ti grade 4 has the highest oxygen content, moderate machinability, the highest mechanical strength of the four types, and is also the most used in the manufacture of implants. However, due to the low overall mechanical strength, the area of application of pure commercial titanium (Cp-Ti) is restricted, at least under intensive stresses and in a severe corrosive environment containing chlorides or fluorides [32–35].

Recent research shows that nanofunctionalised titanium implants with nanostructured surfaces exhibited superior properties (elastic modulus, hardness) [36,37].

Alloying titanium with a variety of elements removes some of these shortcomings by developing alloys with properties controlled by the demands of the application. The alloy Ti-6Al-4V (also called grade 5 titanium), commonly used for the manufacture of implants, is a biphasic alloy ($\alpha + \beta$) that contains 6% Al and 4% V and meets a favorable combination of characteristics [38–40]. The aluminum present in the composition stabilizes the α phase and contributes to its consolidation, and vanadium stabilizes the β ductile phase and ensures the processing capacity of the alloy at high temperatures. However, it has several disadvantages related to, on one hand, its low wear resistance, its high modulus of elasticity, and its low shear strength, and on the other hand, the potential toxicity caused by the presence of Al and V in its composition [41–50]. The improvements brought about by replacing V with Nb and Fe led to two alloys, namely Ti-6Al-7Nb and Ti-5Al-2.5Fe type ($\alpha + \beta$), both with a mechanical behavior comparable to that of the Ti-6Al-4V alloy, but superior to pure titanium (Cp-Ti) [51–58].

Titanium has two crystallographic forms, α and β . At room temperature, pure titanium has a crystallized α phase in the compact hexagonal crystallographic system (hcp), which at a temperature of 883 °C is transformed into the β phase, a cubic crystallographic system with centered volume (bcc). The alloying of titanium with different elements and metallurgical, thermal and/or thermomechanical processing can influence the transformation of both crystallographic structures, depending on their effect on the stability of the two phases, α and β .

Research on the optimization of the composition of titanium alloys has been increasingly intense in recent years, and the most studied alloying elements are: Zr, Ta, Nb, and Mo.

Zirconium is an element with acceptable mechanical strength and good corrosion resistance and biocompatibility [59–63]. It easily forms alloys with titanium whose mechanical properties, depending on the Zr content, can be superior to those of Cp-Ti.

Binary titanium-zirconium alloys have been studied for compositions covering almost the entire range (5–95 wt.% Zr) [26,64–69]. The alloy with 13–17% Zr (Roxolid) that has mechanical, chemical, electrochemical or biological properties superior to titanium or commercial titanium alloys, is still being researched from the point of view of the compositional ratio in order to optimize it. The tensile strength and fatigue resistance of Roxolid alloy were found to be higher than those of pure commercial grade 4 titanium, without reducing tensile elongation or tensile toughness. The biomechanical behavior described by finite element analysis indicated a modulus of elasticity of 103 GPa and generally elastic properties similar to those of the Ti6Al4V alloy. Compared with Ti6Al4V alloy and Cp-Ti, the tensile strength for Roxolid is 953 MPa versus 680 MPa for Ti6Al4V or 310 MPa for Cp-Ti [70–73]. Kobayashi et al. investigated some of the properties of Ti-Zr alloys and showed that up to 50% Zr, the hardness and tensile strength of all alloys were higher than those of Cp-Ti and pure zirconium [74,75].

Niobium is present in titanium alloys, in which it acts as a β phase stabilizing element. The effect of niobium has been studied in binary alloys, although it is more present in ternary alloys such as Ti-6Al-7Nb [76]. Binary alloys containing less than 10% Nb have been shown to have good mechanical properties. The hardness, yield strength and tensile strength of these alloys usually exceed those of Cp-Ti [77]. Lee et al. studied binary Ti-Nb alloys with up to 35% Nb by analyzing their corrosion behavior, mechanical and microstructural properties [78]. A general conclusion from the study of binary titanium alloys is that most alloys with less than 20% alloying elements such as: Zr, In, Ag, Cu, Au, Pd, Nb, Mn, Cr, Mo, Sn and Co have a high potential as implant materials, due to their good

mechanical properties, without compromising biocompatibility and biological behavior, compared to Cp-Ti [79].

The alloying of titanium with more than two carefully selected elements has generated (multicomponent) alloys, which, properly processed, have biomechanical properties at values close to the properties of human tissues [80–82]. Ideally, the alloys should have a low modulus of elasticity, combined with high strength and good fatigue resistance, but most biomedical alloys for implantable devices have a much higher modulus of elasticity than that of hard tissues. Recent studies have shown that the modulus of elasticity of type α titanium alloys and some type alloys ($\alpha + \beta$) is much higher than that of human bone [83–86]. Achieving the right balance between strength and stiffness is still a challenge in designing optimized alloy compositions.

Type β titanium alloys are today intensively researched and widely developed [87,88]. The low modulus of elasticity of these alloys is characteristic of the crystallized β phase in the internally centered cubic system (bcc), with the modulus of elasticity lower than that of the crystallized α phase in the compact hexagonal system (hcp). Of the alloys of this type (Ti-15Mo, Ti-13Nb-13Zr, Ti-12Mo-6Zr-2Fe, Ti-35Nb-5Ta-7Zr and Ti-29Nb-13Ta-4,6Zr) [89–92], Ti-Nb-Ta-Zr is representative, whose modulus of elasticity has values of 48–55 GPa, about half of the modulus of elasticity of the Ti-6Al-4V alloy type ($\alpha + \beta$) of about 113 GPa, or of Cp-Ti with values of 102–104 GPa. Type β titanium alloys mainly contain Nb or Ta (β phase stabilizers) and neutral elements such as Zr or Sn. Although they have a modulus closer to bone (cortical bone has 10–30 GPa) and are biocompatible by alloying only highly compatible elements, their mechanical properties, such as wear resistance and strength under load conditions, are weak [93].

In this context, research into the development of new titanium alloys continues, with clear objectives defined by the current state of research and, more importantly, by the top results regarding the performance of existing materials with the same purpose. Designing new compositions to optimize the tissue compatibility of dental implants remains an ongoing topic. The goal is to achieve a major objective: increasing the success rate by shortening the post-implantation healing period and by enhancing the durability and longevity of the implant.

2. Materials and Methods

Four types of titanium-based alloys were designed, whose compositions contain non-toxic elements. Samples from the experimental alloys (cast bars) were analyzed by scanning electron microscopy (SEM/EDS) for surface morphology evaluations and chemical composition evaluations. Scanning electron microscopy (SEM) was performed with the Thermo Fisher Quattro S equipment (Thermo Fisher Scientific, Waltham, MA, USA). For the microstructural analysis, two samples were sectioned from each titanium bar: one longitudinal and one transverse, in order to perform metallographic investigations. The cross-sections were prepared to highlight the morphology of the crystalline grains and the grain boundaries in the cross-sectional plane, while the longitudinal sections were examined to assess the elongation and orientation of the grains in relation to the processing direction. The samples were embedded in epoxy resin, followed by a metallographic preparation that involved grinding with silicon carbide abrasive papers with gradually increasing grit, ranging from 100 to 1200. Polishing was carried out on cloth plates using diamond suspensions with grits of 9 μm , 6 μm and 3 μm , and finally with colloidal silica. As metallographic reagents were used Keller's reagent: 2 mL HF, 3 mL HCl, 5 mL HNO₃, 190 mL distilled water and Kroll's reagent: 10 mL HF, 30 mL HNO₃, 50 mL distilled water (diluted in some cases additionally with distilled water, for a better highlighting of the microstructure). Microstructural observations were made with an Axio Vert.A1 MAT MAT inverted optical microscope (Carl Zeiss Microscopy GmbH, Jena, Germany) for

metallographic analysis in reflected light, equipped with a Nikon DS-Fi3 microscope camera (Nikon Europe B.V., Amstelveen, The Netherlands), at magnifications of $\times 50$, $\times 100$, $\times 200$ and $\times 500$.

For the study of the influence of the chemical composition on the physico-mechanical characteristics, HV hardness, mechanical tensile strength, yield strength, elongation and modulus of elasticity were determined by standardized methods. For tensile testing, test specimens with a sample length of 15 mm and a diameter of 3 mm were prepared to comply with the dimensional criteria specified in ASTM E8/E8M-22 and EN ISO 6892-1:2009, maintaining proportionality to the standard reference samples [94,95]. Room temperature tensile tests on these undersized samples were performed in accordance with EN ISO 6892-1:2009, using an Instron 3369 universal two-column testing machine (Instron, Norwood, MA, USA) equipped with a 50 kN load cell. Strain measurement during the initial phase was performed using a dynamic extensometer (Instron, Norwood, MA, USA), equipped with a 10 mm gauge length, class 0.5% accuracy. All samples were subjected to a two-phase strain rate measurement protocol along the gauge length. Initially, a low rate of $\dot{\epsilon} = 0.00025 \text{ s}^{-1}$ was applied while the extensometer was attached.

Following the recording of the yield strength (YS), the extensometer was removed, and the strain rate was increased to $\dot{\epsilon} = 0.0067 \text{ s}^{-1}$ until fracture. For tensile testing, a dedicated clamping device was used to support the specimens and allow the correct positioning of the extensometer between the handles of the testing machine. The bars, semi-finished with a diameter of 7.5 mm in the receiving state (not heat-treated), were machined into tensile specimens with a gauge diameter of 3 mm. To prevent slippage during testing, threaded ends were integrated into the specimen design for direct fixation in the test apparatus. A custom fixture was used to accommodate the non-standard geometry, consisting of a threaded connector, a T-end adapter, and an upper holder, ensuring axial alignment during loading. Axial strain was measured using an extensometer mounted on the gauge section.

To evaluate the Vickers hardness, all specimens were metallographically prepared by grinding and polishing to obtain a smooth, defect-free surface suitable for indentation. Hardness measurements were performed using a universal M4C G3 hardness testing machine (EMCO-TEST Prüfmaschinen GmbH, Kuchl, Austria) according to ISO 6507-1 (Metallic Materials—Vickers hardness Test—Part 1: Test Method) [96]. Each sample was tested in three different locations on the cross-section to ensure reproducibility and to take into account possible microstructural inhomogeneity. For each indentation, the diagonal lengths of the impression were accurately measured using an Axio Vert.A1 MAT optical microscope equipped with a Nikon DS-Fi3 microscope camera. The Vickers hardness value was calculated based on the applied load and the measured diagonals. The tests were carried out using a Vickers hardness machine equipped with a diamond pyramid indenter. A constant load of 10 kgf (HV10) was applied for a dwell time of 10 s. The mean hardness value was determined by averaging the results obtained from the three indentations for each sample.

3. Results

3.1. Compositional Analysis of Ti1–Ti4 Alloys

Chemical composition results for Ti1 alloy are presented in Figure 1.

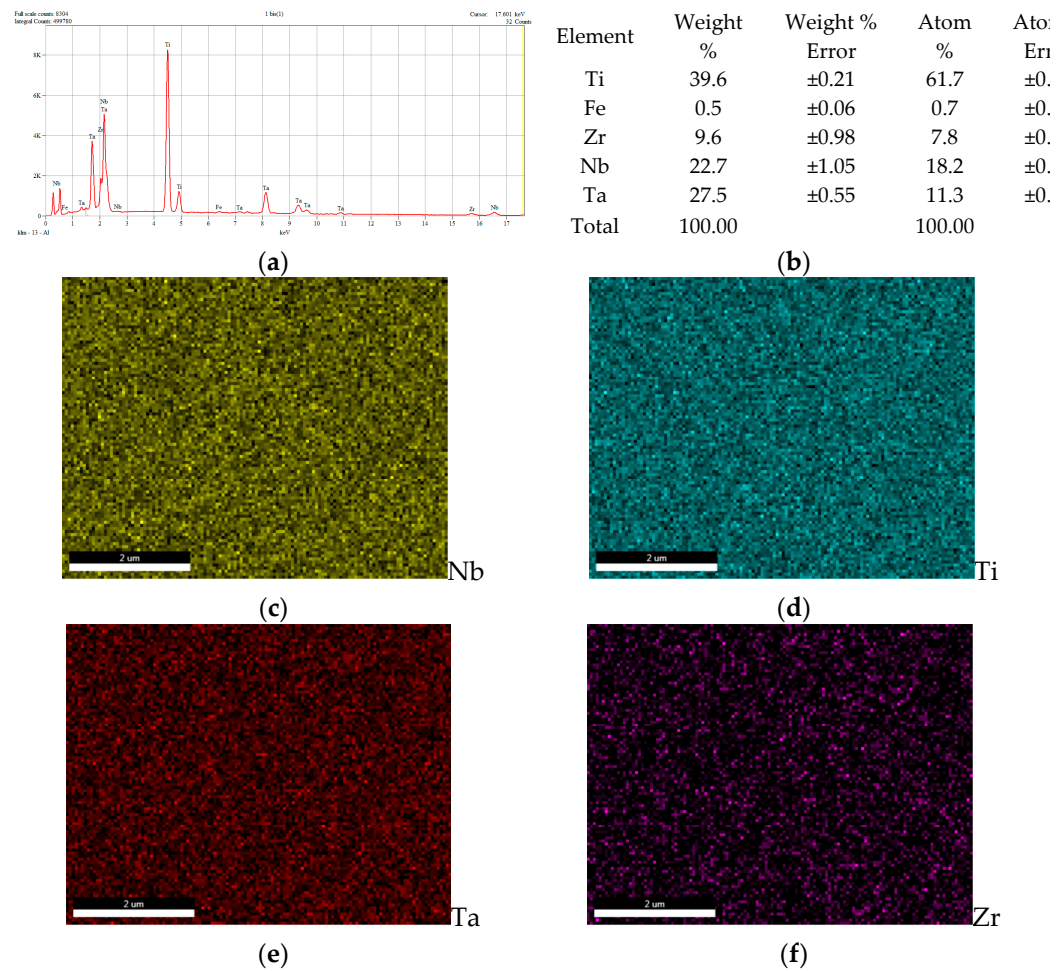
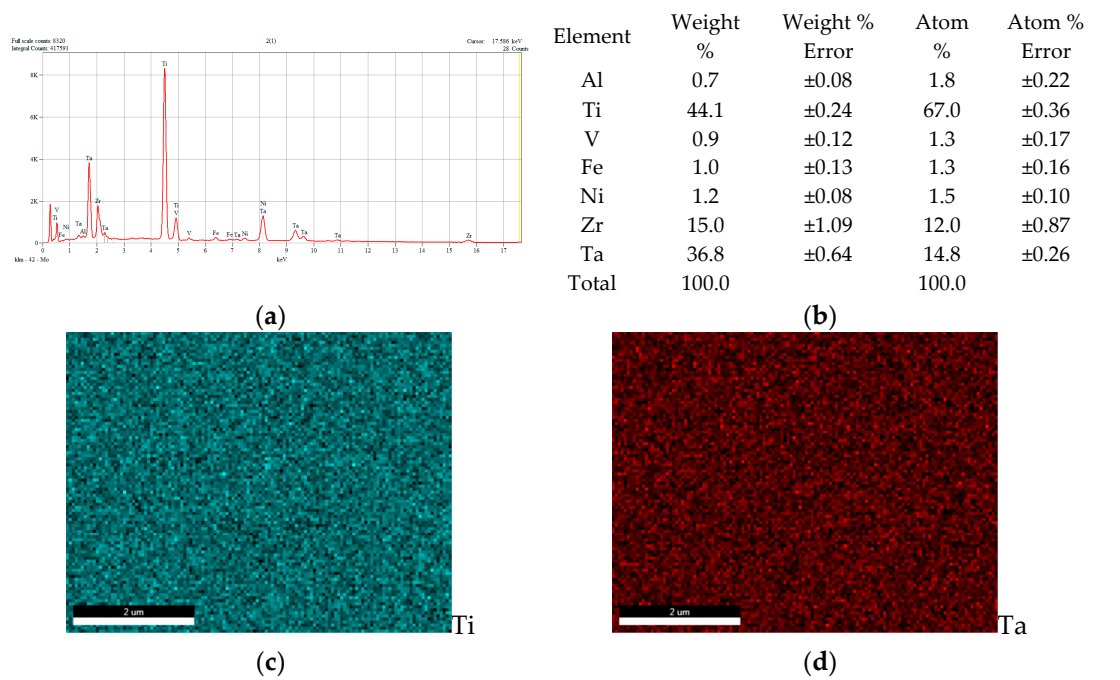


Figure 1. Chemical composition analysis results corresponding to Ti1 alloy: (a) EDS spectra; (b) quantitative results; (c–f) mapping elemental distribution.

Chemical composition results for Ti2 alloy are presented in Figure 2.



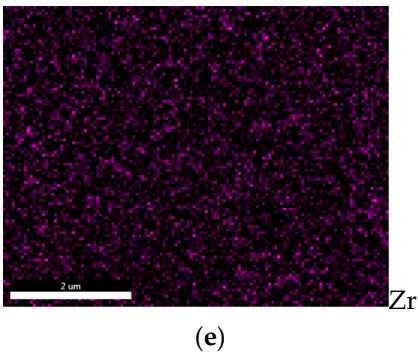


Figure 2. Chemical composition analysis results corresponding to Ti2 alloy: (a) EDS spectra; (b) quantitative results; (c–e) mapping elemental distribution.

Chemical composition results for Ti3 alloy are presented in Figure 3.

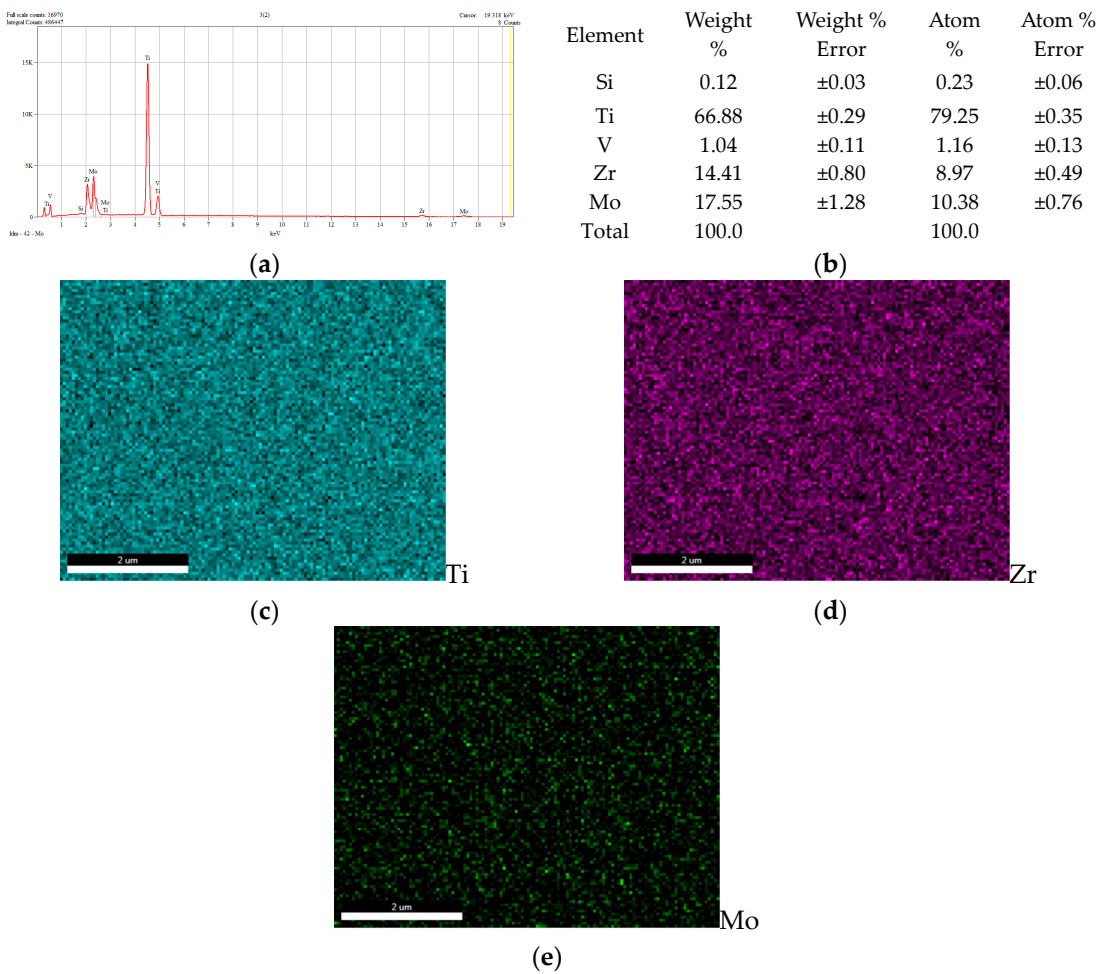


Figure 3. Chemical composition analysis results corresponding to Ti3 alloy: (a) EDS spectra; (b) quantitative results; (c–e) mapping elemental distribution.

Chemical composition results for Ti4 alloy are presented in Figure 4.

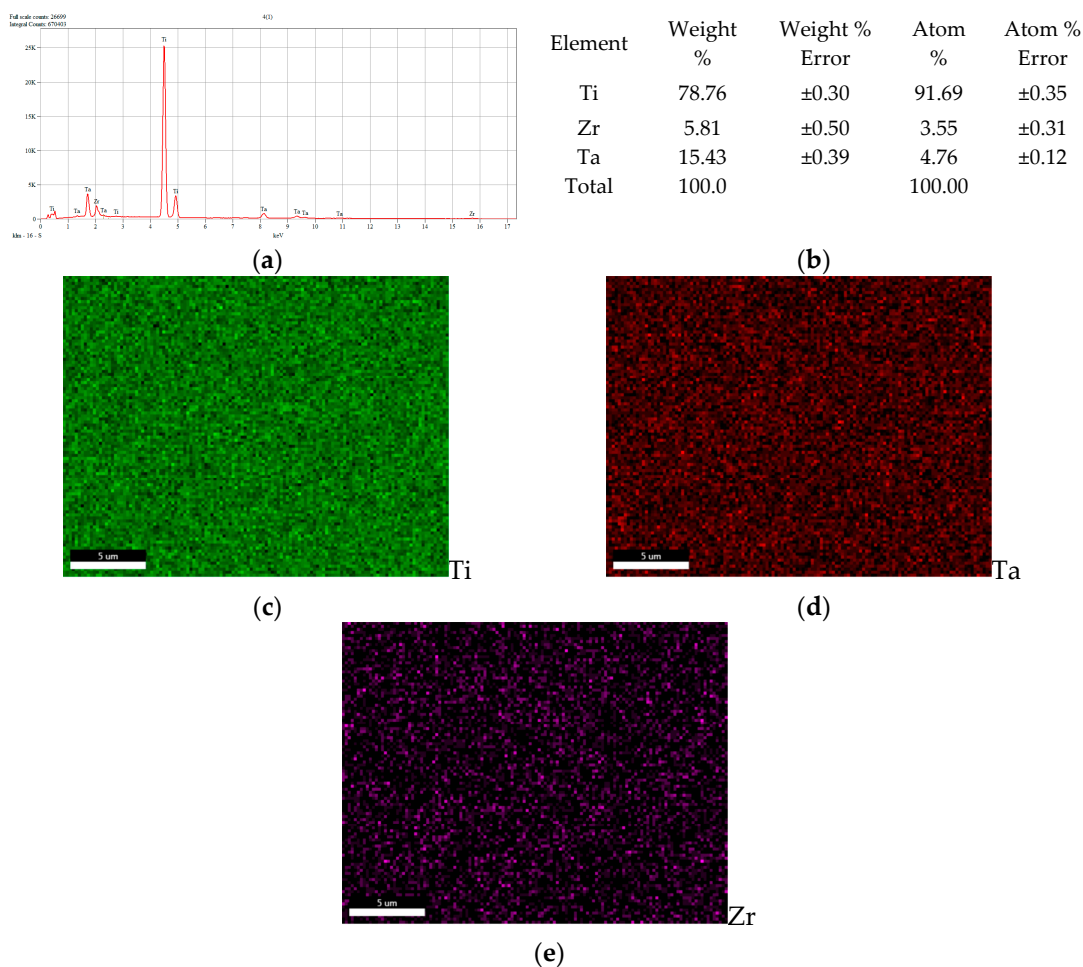
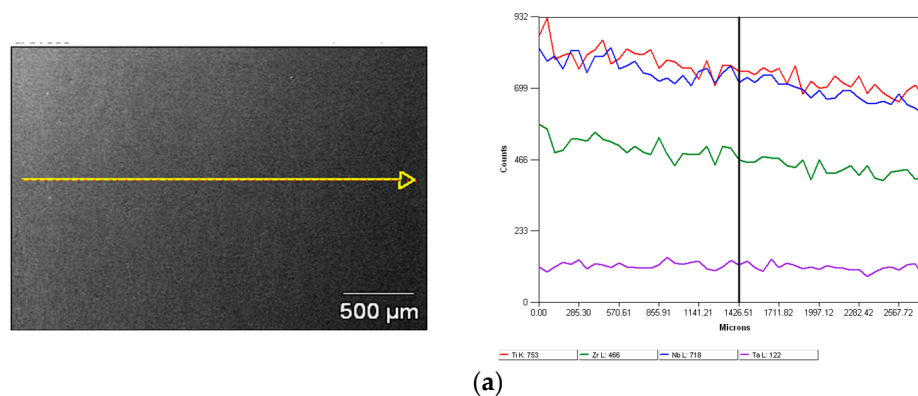


Figure 4. Chemical composition analysis results corresponding to Ti4 alloy: (a) EDS spectra; (b) quantitative results; (c–e) mapping elemental distribution.

3.2. SEM and EDS Analysis of the Surface of Sample from Ti1–Ti4 Alloys

Elemental line profile distribution of the experimental alloys is presented in Figure 5.



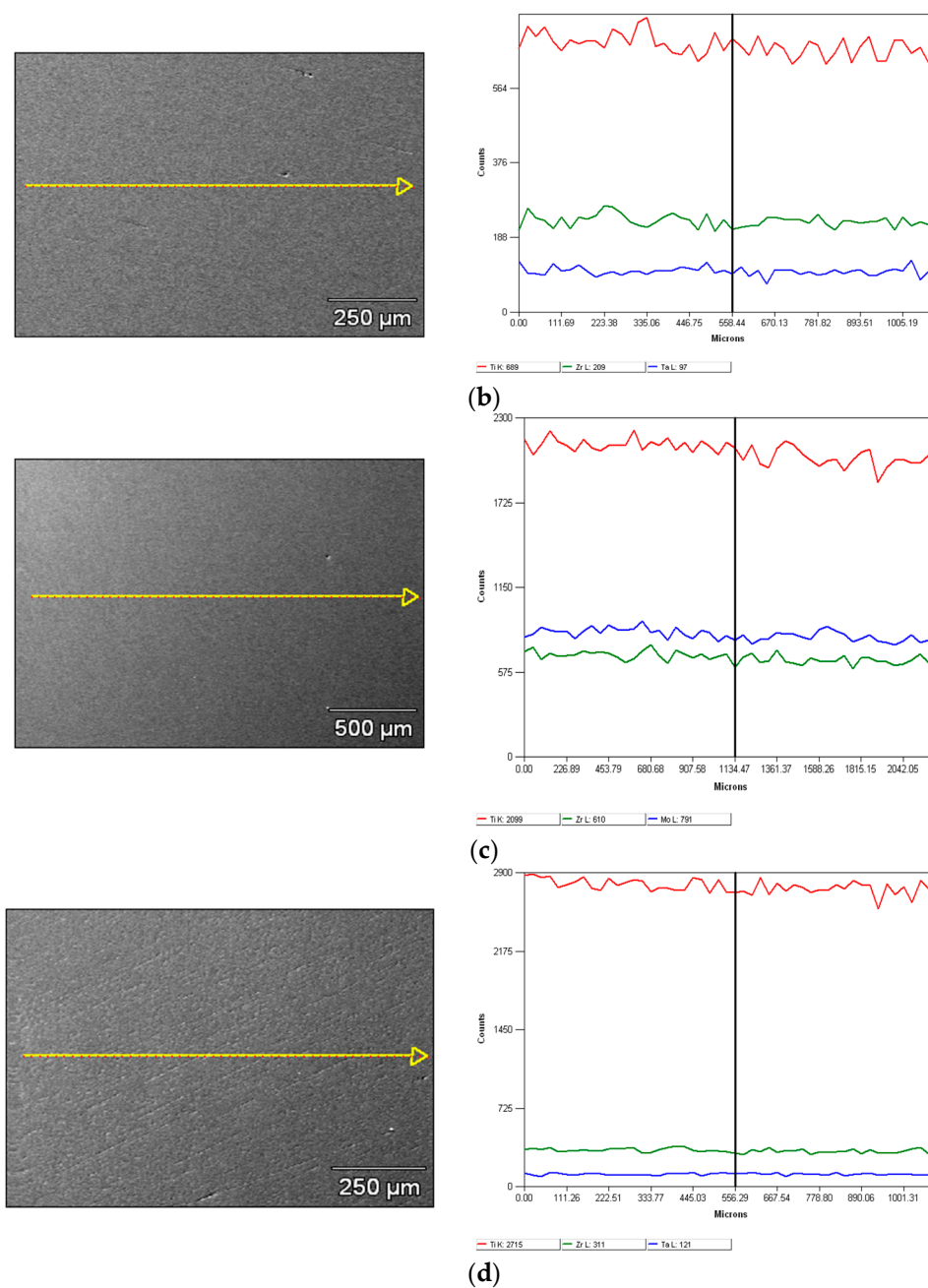


Figure 5. EDS—elemental line profile distribution of the experimental alloys: (a) Ti1; (b) Ti2; (c) Ti3; (d) Ti4; measurement path visible along the dotted red line.

Chemical compositions of Ti1–Ti4 alloys was centralized in Table 1.

Table 1. Chemical composition of alloys—centralized: Ti1, Ti2, Ti3, Ti4.

Elements wt.%	Alloys			
	Ti1	Ti2	Ti3	Ti4
Ti	39.60 ± 0.21	44.16 ± 0.24	66.88 ± 0.29	78.75 ± 0.30
Fe	0.56 ± 0.06	1.03 ± 0.13	-	-
Zr	9.64 ± 0.98	15.05 ± 1.09	14.41 ± 0.80	5.81 ± 0.50
Ta	27.50 ± 0.55	36.85 ± 0.64	-	15.44 ± 0.39
Mo	-	-	17.55 ± 1.28	-
Si	-	-	0.12 ± 0.03	-
Al	-	0.71 ± 0.08	-	-
Ni	-	1.29 ± 0.08	-	-
V	-	0.91 ± 0.12	1.04 ± 0.11	-

Nb	22.70 ± 1.05	-	-	-
Total	100	100	100	100

3.3. Analysis of the Crystallographic Structure of the Alloys by X-Ray Diffraction (XRD)

The XRD analysis presented in Figure 6 reveals the most significant phase structure as follows: (a) β type alloy with unique cubic symmetry structure defined by crystal lattice parameters (Miller indices (hkl) specific to the β -Ti phase, the β phase, stable at room temperature is stabilized by the alloying elements present in the composition Ta, Nb, Fe—the strong stabilizers of the β phase; (b) $\alpha + \beta$ type alloy, an combined content of α -Ti and β -Ti phase stabilizers with stabilizing elements β (Ta, V, Fe, Ni), α -Ti phase stabilizing elements Al and Zr as neutral element; oxides are also present as TiO_2 and Ta_2O_5 ; (c) β type alloy, with a single phase of cubic symmetry identified with the integration of the component chemical elements into a network defined by the lattice parameters and Miller indices of the atomic planes; Mo and V—potent phase β stabilizers (bcc), Zr-neutral, Si-minor influence; (d) $\alpha + \beta$ type alloy, with a Ta content as stabilizer of the β -Ti phase, Zr-neutral, and due to the large amount of Ti and the moderate content of Ta, a α -Ti phase ratio can be maintained.

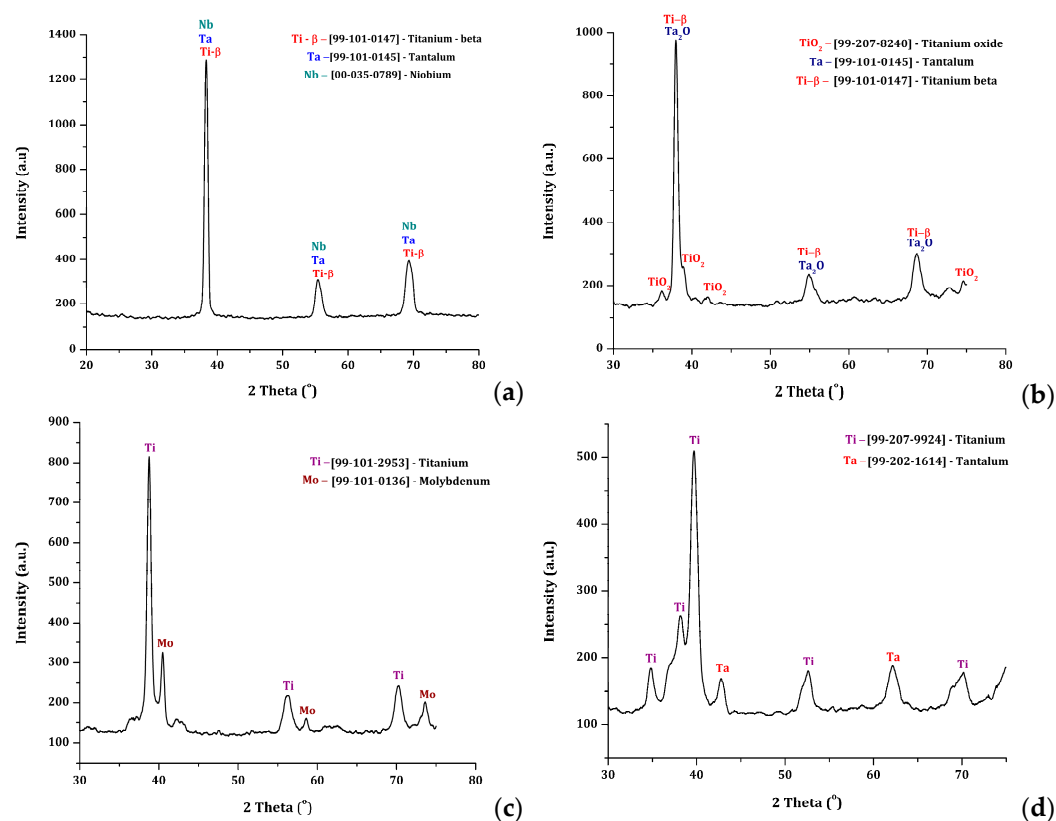


Figure 6. XRD analysis of experimental alloys (phase structure identification): (a) Ti1; (b) Ti2; (c) Ti3; (d) Ti4.

3.4. Optical Microscopy Analysis

Microstructural aspects of samples taken from cast bars of experimental alloys Ti1-Ti4 is presented in Figure 7.

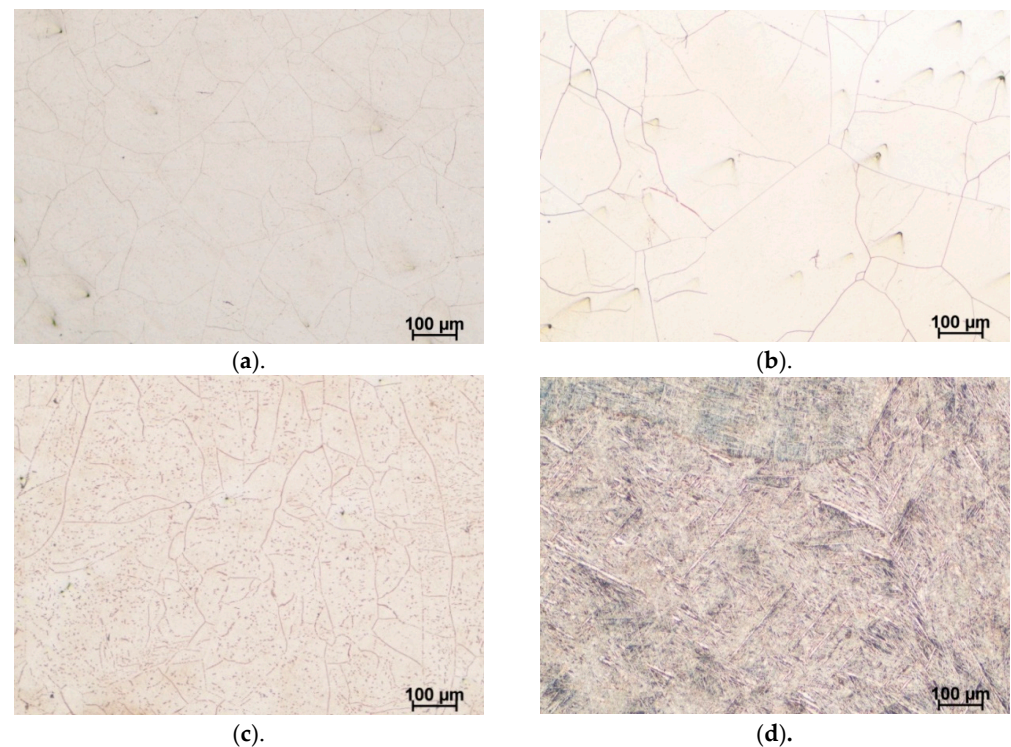


Figure 7. Microstructural aspects of samples taken from cast bars (7 × 65 mm) of experimental alloys: (a) Ti1; (b) Ti2; (c) Ti3; (d) Ti4 (magnification: ×100).

3.5. Tensile Test of Experimental Alloys Ti1–Ti4

Stress-strain diagrams are presented in Figure 8, while the tensile test parameters are shown in Table 2 for experimental alloys Ti1–Ti4.

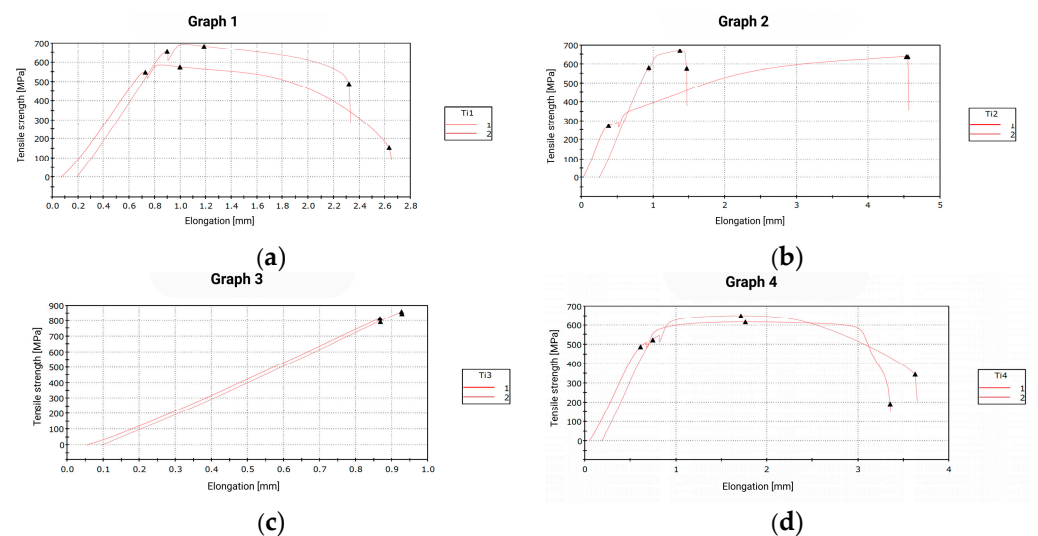


Figure 8. Stress–strain diagram for experimental alloys: (a). Ti1; (b).Ti2; (c).Ti3; (d).Ti4; the black triangles correspond to the measured data points, while the red line is the fitted trendline.

Table 2. Specimen tensile test parameters of experimental alloys: (a). Ti1; (b). Ti2; (c). Ti3; (d). Ti4.

		Tensile Strength [MPa]	Load at Tensile Strength [kN]	Module (Young's Tensile Stress 10 MPa–400 MPa) [GPa]	Yield Strength (Offset 0.2%) [MPa]
(a).	1	575.40	4.07	75.68	549.39
	2	682.73	4.68	85.10	653.98

(b).	1	636.15	4.39	84.51	272.33
	2	667.88	4.83	72.38	580.80
(c).	1	815.16	5.83	95.11	792.27
	2	859.78	6.15	99.82	847.07
(d).	1	615.16	4.35	82.19	488.31
	2	648.86	4.65	90.78	523.50
		Load at Yield (Offset 0.2%) [kN]	Tensile stress at Break (Standard) [MPa]	Load at break (Standard) [kN]	Elongation at Break (Standard) [mm]
(a).	1	3.89	156.41	1.11	2.63100
	2	4.49	490.17	3.36	2.18806
(b).	1	1.88	636.10	4.39	4.54725
	2	4.20	577.33	4.17	1.24119
(c).	1	5.67	815.16	5.83	0.86637
	2	6.06	859.78	6.15	0.88575
(d).	1	3.45	193.82	1.37	3.35144
	2	3.75	345.41	2.47	3.46125

3.6. Vickers Hardness Test

Indentation during hardness tests is shown in Figure 9, and the values obtained are presented in Table 3 for the experimental alloys Ti1–Ti4.

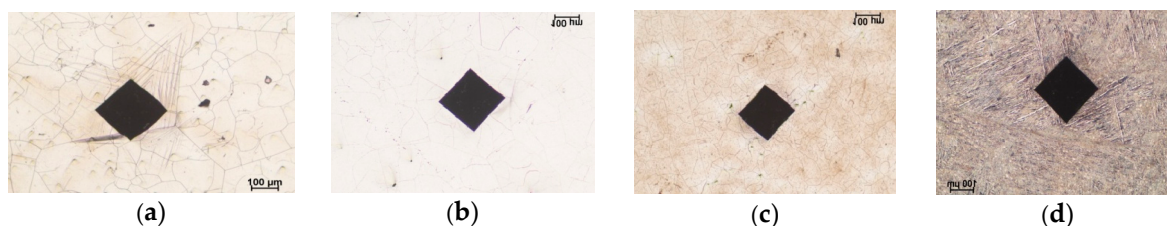


Figure 9. Indentation during hardness HV10 testing (a). Ti1, (b). Ti2, (c). Ti3, (d). Ti4.

Table 3. Vickers hardness (HV10) values for Ti1–Ti4 experimental alloys.

Vickers Hardness HV10	Ti1	Ti2	Ti3	Ti4
#1	257	248	317	237
#2	250	243	334	235
#3	246	249	321	230
Mean Value	251	247	324	234
Standard deviation	4.63	2.35	7.59	3.10

Mechanical properties values are presented in Table 4, while their variations are depicted in Figures 10–13.

Table 4. Experimental data processing. Values of the mechanical properties of Ti1–Ti4 experimental alloys.

Samples	Ti1		Ti2		Ti3		Ti4	
	T1.1.	T1.2.	T2.1.	T2.2.	T3.1.	T3.2.	T4.1	T4.2.
D [mm]	3.002	2.955	2.964	3.034	3.018	3.0145	3.001	3.022
G [%]	27.8	25.7	19.2	1.9	0.3	0.3	27.2	38.9
A5 [%]	13.3	8	20.2	7.2	2.2	2.9	12.7	18.7
Rm [MPa]	575	683	636	668	815	860	615	649
Rp [MPa]	549	654	581	581	792	847	488	523
E [GPa]	76	85	85	72	95	100	82	91

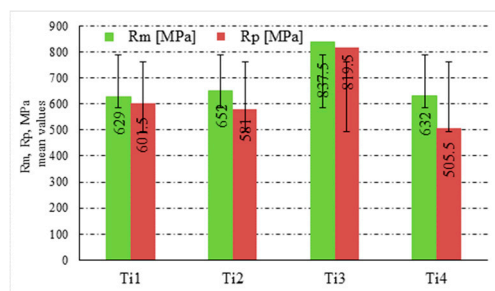


Figure 10. Variation in mechanical strength properties (Rm, Rp) as a function of the type of alloy.

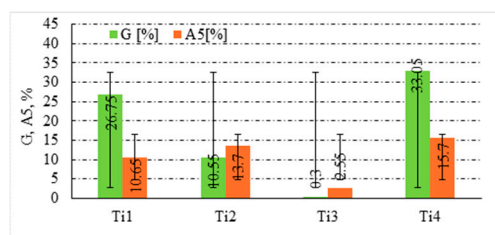


Figure 11. Variation in the mechanical properties of plasticity–ductility (A5, G) as a function of the type of alloy.

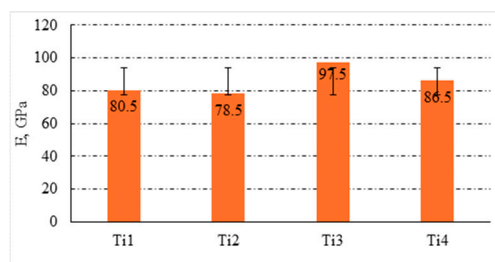


Figure 12. Variation in modulus of elasticity as a function of the type of alloy.

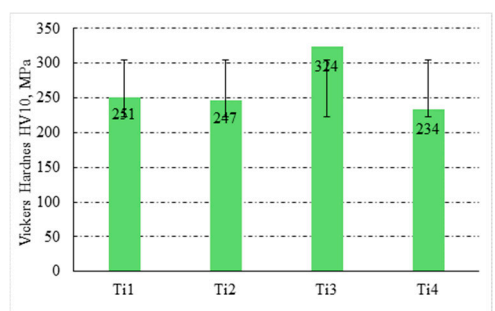


Figure 13. Variation in Vickers hardness as a function of alloy type.

To facilitate a comprehensive understanding of the values obtained for the mechanical properties of the experimental alloys, a comparison has been presented in Table 5.

Table 5. Comparison between the mechanical properties of experimental alloys (Ti1–Ti4) and those of conventional alloys (Cp-Ti grades 4 and Ti6Al4V).

Mechanical Properties (Mean Value)	Ti1	Ti2	Ti3	Ti4	Cp-Ti Grd4 (*)	Ti6Al4V (*)
Rm [MPa]	629	652	837.5	632	550	900
Rp [MPa]	601.5	581	819.5	505.5	480	850
E [GPa]	80.5	78.5	97.5	86.5	104	113
A5 (%)	10.65	13.7	2.55	15.7	15	10

* Nicholson, J.W. Titanium Alloys for Dental Implants: A Review. *Prosthesis* **2020**, *2*, 100–116. <https://doi.org/10.3390/prosthesis2020011> [31].

The variations in the mechanical properties of the experimental alloys (Ti1–Ti4) and those of the conventional alloys (CP-Ti Grades 4 and Ti6Al4V) are illustrated in Figures 14–16.

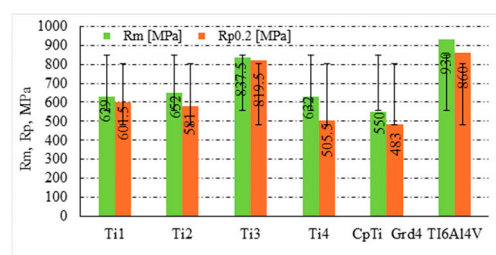


Figure 14. Tensile strength and yield strength based on the type of alloy.

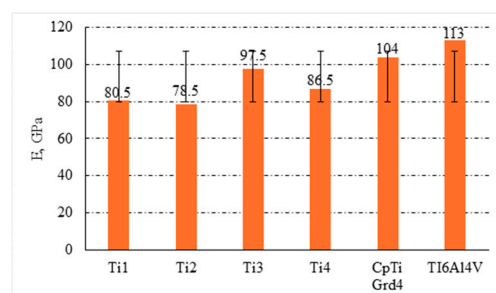


Figure 15. Modulus of elasticity as a function of the type of alloy.

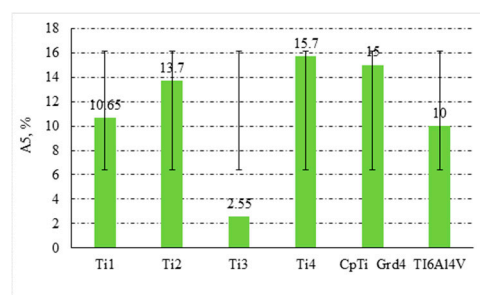


Figure 16. Elongation at break according to the type of alloy.

4. Discussion

Titanium and some titanium-based alloys are metal biomaterials frequently used to make dental implants due to their physical and biological characteristics, and also due to the performance obtained in improving mechanical properties, either by alloying or by proper processing.

Biomechanical compatibility or functional biocompatibility is a fundamental requirement of alloys, which need a higher level of strength than that of bone and a modulus of elasticity close to that of human bone.

Achieving an appropriate balance between strength and stiffness is an essential objective in the research and development of new alloys, with a low modulus of elasticity to avoid the stress shield effect in bone fixation, combined with a high strength, necessary in conditions of hard tissue replacement and specific stresses. Exceeding the usage limits of Cp-Ti, at least in the case of intensive demands, involved adopting solutions such as alloying titanium with different elements, which over time led to the development of alloys with improved mechanical properties [45].

The best known dental implant is the Ti6Al4V type $\alpha + \beta$ alloy, whose use is disputed, mainly, on considerations regarding the potential cytotoxicity of the Al and V elements present in the composition of the alloy.

In fact, the elimination of elements with potential toxicity from the composition of biomedical alloys is a topic of interest, being a priority in current approaches in the research of new alloys for dental implants, along with the requirements regarding their mechanical behavior, defined by the strength properties and the modulus of elasticity. Regarding the latter characteristic, several studies have recently shown that the modulus of elasticity of type α Ti-based alloys and some $\alpha + \beta$ alloys is much higher than that of human bone, which can cause, through the shielding effect of bone stress, a poor osseointegration of the implant [4,72–76].

From this point of view, type β titanium alloys are today intensively researched and developed on a large scale [77,78]. These are generally biocompatible alloys containing mainly Nb or Ta (β phase stabilizers) and neutral elements such as Zr or Sn [79–83]. The low modulus of elasticity of these alloys is characteristic of the β phase, crystallized in the internally centered cubic system (BCC), with a lower modulus of elasticity than that of the α phase, crystallized in the compact hexagonal system (HCP).

The Ti-Nb-Ta-Zr system (β alloys), with modulus of elasticity values of 48–55 GPa, has about half the modulus of elasticity of the Ti-6Al-4V alloy type ($\alpha + \beta$), at about 113 GPa, or of the CP-Ti, with a modulus of elasticity of 102–104 GPa [30,31].

However, it is estimated that although they have a modulus closer to that of bone (10–30 GPa for cortical bone) and are biocompatible by alloying only with highly compatible elements, the properties of these alloys, such as wear resistance and strength under load conditions, are weak [84,88].

The research carried out on the four compositions designed to respond to the current priorities in the development of new biocompatible Ti-based alloys provides data that establishes a link between the chemical composition (type of alloying elements and their content in the alloy), the phase structure, and the physico-mechanical properties of the experimental alloys. The measured values of the main characteristics of strength (R_m , R_p , VH), plasticity–ductility (A_5 , G), and also those of the modulus of elasticity (E) were compared with those of the current metallic materials frequently used for the realization of dental implants (Cp-Ti grade 4 and Ti6Al4V). The detailed analysis of the characteristics of each alloy separately and in comparison with conventional metal materials highlights the following aspects:

- The highest values of mechanical tensile strength (837.5 MPa) and yield strength (819.5 MPa) characterize the alloy with the Ti3 composition, which also has the highest strength/modulus of elasticity ratio (8.58). It has the highest hardness (324VH₁₀) of the experimental alloys and the highest modulus of elasticity (97.5 GPa). The alloy has no plasticity, with the elongation (A_5) and tear stress (G) values being the lowest ($A_5 = 2.55\%$ and $G = 0.33\%$). In terms of mechanical strength properties, Ti3 alloy is superior to Cp-Ti grade 4 and comparable to Ti6Al4V alloy.
- Alloys with the compositions Ti2, Ti4, and Ti1 differ from Ti3 in terms of mechanical properties (R_m and R_p). These are characterized by balanced values that are very close to each other, varying within the following limits: $R_m = 629\text{--}652$ MPa and $R_p = 505.5\text{--}601.5$ MPa. The alloys have superior Cp-Ti grade 4 mechanical properties, but they are significantly lower than both the experimental alloy with the Ti3 comp and the conventional Ti6Al4V alloy.
- The Ti4 composition alloy is the most ductile of the alloys, characterized by elongation at break $A_5 = 15.7\%$ and neck at break or stricture $G = 33.05\%$. It is followed by the Ti1 alloy, with elongation at break $A_5 = 10.65\%$, and $G = 26.75\%$. Of note, the elongation at break of the Ti2 alloy is comparable to the Cp-Ti grade 4 and superior to the Ti6Al4V alloy.
- The modulus of elasticity of the studied alloys has values in the following range: 78.5–97.5 GPa. The highest value characterizes the Ti3 alloy (97.5 GPa), followed by

the Ti4 alloy (86.5 GPa), and the lowest value is characteristic of the Ti2 alloy (78.5 GPa) close to Ti1 (80.5 GPa).

Analyzed in comparison with Cp-Ti grade 4 and Ti6Al4V, the experimental alloys (Ti1–Ti4) can be characterized as follows:

- The mechanical strength properties (R_m and R_p) are higher than those of pure commercial titanium (Cp-Ti grade 4) for all compositions: Ti1–Ti4, but slightly lower than those of alloy Ti6Al4V;
- The plasticity–ductility properties have values comparable to those of Cp-Ti grade 4 (Ti4 and Ti2 compositions) and Ti6Al4V (Ti1 composition), with one exception, the Ti3 alloy.
- All four experimental alloys have a lower modulus of elasticity than Cp-Ti grade 4 (102–104 GPa) and Ti6Al4V (113 GPa), commonly used in dental implants.

With regard to the criteria underlying the selection of the alloy for the manufacture of dental implants, namely, high mechanical strength (high R_m and $R_{p0.2}$) to withstand chewing forces, optimum hardness (HV) to prevent wear but without becoming too brittle, sufficient ductility (high elongation, A%) to allow processing and adaptation to the biomechanical conditions of the bone, a low modulus of elasticity to avoid the shielding effect of bone stress and to ensure good osseointegration, we conclude that alloys with the Ti3 composition can be used in applications that require intensive stress; alloys with Ti4, Ti2 and Ti1 compositions are appreciated as balanced and have a favorable combination of mechanical strength and plasticity. Although all the compositions tested describe alloys with a lower modulus of elasticity in value compared to conventional alloys (Cp-Ti grade 4 and Ti6Al4V), it is worth noting the value of 78.5 GPa, characteristic of the Ti2 composition, followed immediately by Ti1 with 80.5 GPa. The favorable combination of mechanical strength and modulus of elasticity is demonstrated by the composites Ti2, Ti4, and Ti1.

However, taking into account the aspects related to biological compatibility (Ti2 may be less suitable due to the presence of the elements Ni, Al, V, and Fe), we recommend the Ti4 and Ti1 compositions as viable, with the mention that the Ti4 alloy has an optimal composition from an economic point of view (alloying titanium only with zirconium and tantalum in the following proportions: Ti-78, 8%, Zr-5.81%, Ta-15.44%).

In conclusion, Ti1 and Ti3 stand out as promising candidates, with each of the compositions recommended for specific clinical situations in dental implantology, due to their structure, properties, and the absence of toxic elements.

Although it reveals useful information, this study has limitations related to the lack of detailed analysis of the influence of alloying elements in the composition, or a comparative analysis from which to more clearly determine the contribution of Mo in the Ti-Zr-Mo composition versus Ti-Zr. Of course, all these will be the subject of future studies, when the characterization of the experimental alloys will be completed with data obtained from corrosion behavior analysis in environments that simulate the oral environment and cellular behavior. A comprehensive characterization of the alloys can more rigorously support the selection of some of them for progressing to a higher level of testing. Research is currently underway regarding the development of dental implants, determining some practical utility characteristics (e.g., fatigue resistance, wear resistance, etc.) and the capacity for osseointegration, through in vivo testing of implants made from some of the experimental alloys.

5. Conclusions

Research on the development of new titanium alloys by optimizing their composition considers the basic requirements regarding the biological tissue compatibility and also the mechanical, functional biocompatibility of the dental implant.

This research carried out on four compositions of experimental alloys provides data of practical utility in the selection of titanium alloys with compositions appropriate for the type of demand for specific clinical situations.

The compositions in which the combination and proportion of the alloying elements present contribute to an increase in mechanical resistance properties (R_m , R_p), such as Ti3 (66.88%Ti, 14.41%Zr, 17.15%Mo), indicated in conditions of intense stress, were highlighted.

On the other hand, there are compositions that describe highly ductile alloys, such as Ti4 (78.75%Ti, 5.81%Zr, 15.44%Ta), which are easy to process and adjust for customized implants.

Alloys with a high content of Nb and Ta, such as Ti1 (39.6% Ti, 9.6% Zr, 22.7% Nb, 27.5% Ta), offer the most balanced combination of mechanical strength, ductility–plasticity and elasticity modulus. A more comprehensive characterization, which also includes information regarding corrosion behavior and cell testing, can support the selection of some of the four experimental alloys analyzed.

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