Online ISSN 2559 – 1061 Volume 10, Number 2/2025

COMPARATIVE STUDY ON COMMERCIALLY Ti-6Al-4V AND Ti-Mo ALLOYS FOR IMPLANTS

Andrei Victor SANDU[1,2], Madalina Simona BALTATU[1], Andrei PRUTEANU[1], Petrica VIZUREANU[1,2]

Abstract. *Titanium-based alloys are widely used in biomedical applications due to their excellent biocompatibility, corrosion resistance, and favorable mechanical behavior. This study provides a comparative analysis of the commercial Ti-6Al-4V (Grade 5) alloy and a newly developed β-stabilised alloy, Ti15Mo7Zr15Ta5Nb, with the aim of assessing their suitability for orthopedic implants. The materials were fabricated through conventional processing (Ti-6Al-4V) and vacuum arc remelting (Ti15Mo7Zr15Ta5Nb), followed by detailed microstructural, structural, and mechanical characterization. Optical microscopy and X-ray diffraction revealed a bimodal α+β microstructure for Ti-6Al-4V, whereas Ti15Mo7Zr15Ta5Nb exhibited a predominantly β-phase structure with orthorhombic α" martensite. Nanoindentation tests indicated that the experimental alloy possesses a significantly lower elastic modulus (40.35 GPa) compared to Ti-6Al-4V (113.8 GPa), reducing the risk of stress shielding and improving biomechanical compatibility with human bone. Although Ti-6Al-4V showed higher hardness, the new alloy demonstrated superior elasticity and compositional biocompatibility due to the absence of Al and V. Overall, Ti15Mo7Zr15Ta5Nb emerges as a promising alternative for next-generation orthopedic implants, offering improved biological safety and mechanical compatibility, while Ti-6Al-4V remains favorable for applications requiring high strength.*

Keywords: biocompatibility; microstructure; titanium alloys; tribological properties; β-stabilized alloys

DOI 10.56082/annalsarsciphyschem.2025.2.115

1. Introduction

Biomaterials are synthetic materials compatible with the human body, with a wide range of properties, which can be transformed into medical devices that correspond to strictly imposed functional parameters. Biocompatible materials are intended to "work under biological constraint" and thereby become adapted to various medical applications. In this context, a biomaterial represents any substance or combination of substances, other than drugs, of synthetic or natural origin, which can be used for an indefinite period, as such or as a component part of a system (device) for the morphological and / or functional reconstruction of tissues, organs.

[1] Faculty of Materials Science and Engineering, "Gheorghe Asachi" Technical University of Iasi, 67 Prof. D. Mangeron Blvd., 700050, Iasi, Romania
[2] Academy of Romanian Scientists, 3 Ilfov St., RO-050044, Bucharest, Romania
*Corresponding authors: andrei-victor.sandu@academic.tuiasi.ro, madalina-simona.baltatu@academic.tuiasi.ro, petrica.vizureanu@academic.tuiasi.ro

Metals and their alloys in human medicine, along with other organic and inorganic materials, have their origins several thousand years ago, but in the last century they have achieved significant clinical success. The use of metallic materials in one or another field of technology depends on the relationship between their structure and properties. The selection of materials used in contact with living cells or tissues for implantation into the human body, that is, biomaterials, is determined primarily by their acceptance by the human tissues with which they interact (biocompatibility) and by their ability to fulfill the functional role for which they were implanted (biofunctionality).

Among the most important factors that affect a biomaterial successfully integrated into the human body are: physicochemical properties, design, biocompatibility, surgical technique applied to implantation and, last but not least, the patient's health.

In order to verify the quality of a biomaterial, a detailed characterization of the material to be used must be made from a mechanical, thermal, chemical, optical, electrical, etc. point of view, in order to establish with certainty, the conditions under which it must be successfully used in the manufacture of the final product. This must meet certain technological and economic requirements that can be followed mainly by analyzing the following factors: composition and structure, properties, performance.

Titanium-based alloys have been widely used in biomedical applications due to their excellent biocompatibility, high corrosion resistance, and favorable mechanical properties. Among these alloys, Ti-6Al-4V has been the most commonly employed in orthopedic and dental implants due to its optimal balance of strength, toughness, and osseointegration capacity. Al improves the mechanical strength and machinability of the alloy, while V increases fatigue strength and hardness. It has high tensile strength and good fatigue resistance, making it ideal for mechanically stressed structural components such as implants and orthopedic devices. It exhibits excellent corrosion resistance due to the formation of a titanium oxide layer on the surface, which protects the metal from the aggressive environment of the human body. It is known for its ability to allow good integration with bone, an important aspect for the long-term success of implants. It is predominantly used in the manufacture of orthopedic implants such as hip and knee replacements, plates and screws for fracture fixation, as well as in dentistry for dental implants. Although it is widely used, there are concerns about the release of Al and V ions into the body, which may have adverse long-term health effects. This has stimulated research into the development of alternative alloys that eliminate these elements or replace them with safer ones. Recent research is focused on the development of Al and V-free titanium alloys, such as Ti-Mo and Ti-Zr alloys, which promise to reduce biological risks and improve biomechanical compatibility and performance [3-5].

This study aims to compare the properties of Ti-6Al-4V and Ti15Mo7Zr15Ta5Nb, assessing their suitability for orthopedic applications. This study is fundamentally aimed at evaluating and comparing the mechanical of Ti-6Al-4V and Ti15Mo7Zr15Ta5Nb alloys to determine their efficacy and safety in orthopedic applications, thereby addressing critical health and technological challenges in biomaterials development and offering more biocompatible and mechanically suitable alternatives for implantation.

2. Materials and methods

2.1. Material fabrication

In this work, two types of titanium-based alloys were used: a commercial one, Ti6Al4V (Grade 5), and an experimental one, Ti15Mo7Zr15Ta5Nb, each obtained by different methods, adapted to the specific purposes of the research.

The commercial Ti6Al4V alloy was purchased from a specialized supplier, in the form of standardized semi-finished products (bar, plate or sheet), according to ASTM B265 and AMS 4911 specifications. This α+β alloy, with a nominal composition of 6% aluminum and 4% vanadium, is recognized for its high mechanical strength, biocompatibility and corrosion resistance, being widely used in the aerospace and medical fields. The material was delivered in annealed condition, ensuring a homogeneous microstructure and stable mechanical properties, suitable for further processing and experimental characterization.

The experimental alloy Ti15Mo7Zr15Ta5Nb was developed in the laboratory by the vacuum arc melting (VAR) method, using high-purity metallic raw materials (Ti - 99.8%, Mo - 99.7%, Zr - 99.2%, Ta - 99.5%, Nb - 99.5%). For each mini-ingot, the melting process was repeated six times, on each side, to refine and homogenize the chemical composition. The technological parameters established for obtaining the experimental titanium-based alloys were the following: melting power of minimum 55 kVA; melting current of minimum 650 A, 60% DS, three-phase voltage; vacuum level of 4.5x10^-3 mbar; inert gas flow rate of 5 l/min. The resulting chemical composition of the titanium-based alloys was determined by EDS analyses, demonstrating that the metallurgical process was correctly and sequentially performed, indicating a precise and homogeneous chemical composition.

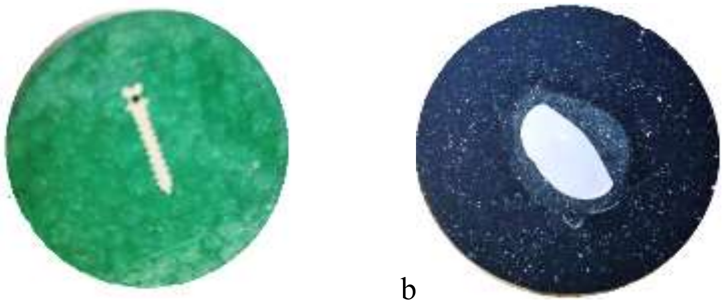
This comparative approach between a standardized alloy and an experimental one allows the evaluation of the influence of the chemical composition and the elaboration method on the final properties of the materials, contributing to the development of new titanium alloys with improved performances for specific applications.

2.2. Sample preparation

For the microstructural analysis of Ti6Al4V and Ti15Mo7Zr15Ta5Nb alloys, the samples were subjected to a rigorous preparation process, consisting of cutting, embedding and grinding, to ensure the obtaining of surfaces suitable for examination and testing of properties by indentation. The samples were cut using the precision cutting machine Secotom from Struers, which provides fast and precise cuts, minimizing deformations and heating of the sample. The cutting was performed under continuous cooling with coolant to prevent structural changes of the material. After cutting, the samples were embedded in a thermoplastic resin using the automated press CitoPress from Struers. This process facilitated the handling of the samples in subsequent steps and protected their edges. The pressing parameters were selected to ensure a uniform and defect-free embedding.

The embedded samples were mechanically ground on a Struers Tegramin grinding and polishing machine, equipped with an automatic arm for sample movement. The grinding was performed in successive steps, using progressively finer grit abrasive paper (from 320 to 1200 grit), to remove scratches and imperfections from the previous step. Each grinding step was performed carefully to ensure a flat and smooth surface, ready for microstructural analysis.

The images in Figure 1 illustrate the samples after the embedding step.



b

Fig. 1. Image of samples: a – Ti-6Al-4V; b – Ti15Mo7Zr15Ta5Nb

2.3. Microstructural characterization methods

For the examination of the microstructure, a high-precision optical microscope Zeiss Axio Imager A1, equipped with multiple objectives (4×, 10×, 20×, 40×, 100×) and HBO illumination source was used. This equipment allows obtaining clear and detailed images of metallographic structures, facilitating the analysis of morphology and phase distribution. To highlight the microstructure, the samples were subjected to an appropriate chemical attack, using a solution composed of hydrofluoric acid, hydrochloric acid and distilled water. This solution allowed for the clear revelation of grain boundaries and phases present in the alloys, essential for a precise microstructural analysis. By using these methods and equipment, a detailed and reliable characterization of the microstructure of Ti6Al4V and Ti15Mo7Zr15Ta5Nb alloys was ensured.

For the investigation of the phase composition and crystalline structure of the titanium-based alloys, X-ray diffraction (XRD) analysis was employed. The measurements were carried out using a PANalytical X'Pert PRO MRD diffractometer, operating with CuKα radiation (λ = 1.5406 Å) at a scanning range of 10°–90° (2θ). This equipment enabled the identification of the dominant crystalline phases (α, β, and α″) present in the alloys, as well as the evaluation of the structural transformations induced by the alloying elements and cooling conditions. The XRD technique proved to be essential for correlating the compositional and microstructural features with the mechanical and functional behavior of the materials under study.

2.4. Mechanical characterization methods

In this work, the mechanical characterization of Ti6Al4V and Ti15Mo7Zr15Ta5Nb alloys was performed using the CETR/Bruker UMT-2 (Universal Micro Tribometer). This versatile equipment allows for a wide range of tribological and mechanical tests, including friction, wear, adhesion and hardness measurements, making it ideal for the analysis of metallic, non-metallic materials and thin films.

To determine the mechanical characteristics, the indentation method was used with a diamond Rockwell indenter, having a cone angle of 120° and a tip radius of 200 μm. A force of 5 N was applied progressively, and the equipment recorded the movement of the diamond tip as it penetrated the material. This method allows the evaluation of the mechanical properties of materials, including hardness and elastic modulus.

The UMT-2 tribometer is also successfully used for the analysis of thin and very thin layers, as well as metallic and non-metallic coatings, to determine their adhesion and mechanical properties. The versatility of the equipment allows adaptation to various test configurations, including scratch, wear and friction tests, under controlled temperature and humidity conditions.

By using the UMT-2 tribometer, a detailed and precise characterization of the mechanical properties of the studied alloys was ensured, contributing to the understanding of their behavior in various applications.

3. Results and discussions

3.1. Microstructure of alloys

Table 1 presents the average chemical composition of Ti15Mo7Zr15Ta5Nb alloy determined by EDX analysis, as well as of the standard Ti-6Al-4V alloy. The values represent the average of ten determinations performed in five different areas of the samples, highlighting the compositional homogeneity and the absence of inclusions.

Table 1. Chemical composition of studied alloys

Aliaj	*Ti [%]*	*Mo [%]*	*Zr [%]*	*Ta [%]*	*Nb [%]*	*Al [%]*	*V [%]*	*Fe [%]*	*O [%]*	*C [%]*	*N [%]*	*H [%]*
Ti-6Al-4V (Grade 5)	89.00	–	–	–	–	6.00	4.00	0.25	0.20	0.08	0.05	0.015
Ti15Mo7Zr15 Ta5Nb	61.55	14.94	7.79	10.45	4.57	–	–	–	–	–	–	–

Figure 2 illustrates the microstructure of Ti-6Al-4V (Grade 5) and Ti15Mo7Zr15Ta5Nb alloys, observed by optical microscopy at a scale of 500 µm. Significant differences are noted between the two microstructures, reflecting both the distinct chemical composition and the nature of the predominant phases in each alloy. The microstructure of the Ti-6Al-4V alloy (Grade 5) is characterized by a lamellar distribution of the α phase (hexagonal), with a typical dendrite-like appearance, specific to cooling from the β domain, accompanied by the presence of the β phase at the boundaries of the α lamellae, highlighted by darker areas; this bimodal structure (α + β) offers an optimal balance between mechanical strength and ductility.

The microstructure of the Ti15Mo7Zr15Ta5Nb alloy is dominated by the stabilized β phase (BCC cubic), highlighted by a network of large grains and internal substructures specific to β phase transformations; at the same time, orthorhombic martensitic textures of α″ type are distinguished, visible through the contrast obtained following chemical attack, suggesting a rapid cooling from the β domain and the formation of the α″ phase under metastable conditions.

Fig. 2. Microstructures of alloys: left - Ti-6Al-4V (Grade 5) and right - Ti15Mo7Zr15Ta5Nb

Figure 3 presents the X-ray diffraction (XRD) patterns for the Ti-6Al-4V (Grade 5) and Ti15Mo7Zr15Ta5Nb alloys, highlighting their distinct phase compositions and microstructural characteristics.

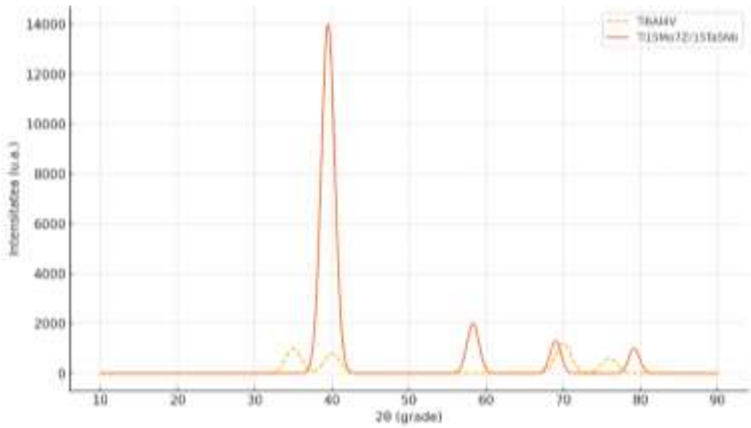


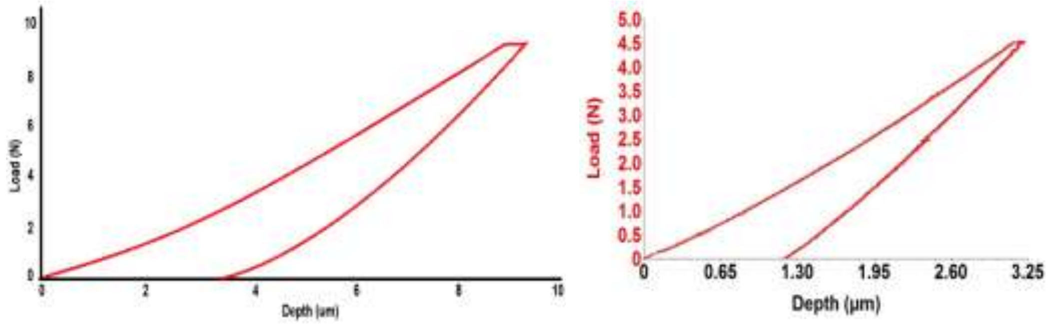
Fig. 3. X-ray diffraction (XRD) patterns

The diffraction pattern for Ti6Al4V shows peaks characteristic of the α phase (hexagonal close packed, HCP), with intense reflections corresponding to the (100), (002), and (103) planes, along with a smaller peak for the β phase (body-centered cubic – BCC). The distribution of these phases is influenced by the cooling after solidification: the α phase is mostly formed during slow cooling, and the β phase is only partially stabilized due to the presence of vanadium, a β-stabilizing element. The resulting texture (α + β phase) gives the Ti6Al4V alloy an excellent combination of mechanical strength and ductility, which is why it is extensively used in the biomedical and aerospace fields.

Ti15Mo7Zr15Ta5Nb is a stabilized β alloy. The XRD pattern of this alloy shows a prominent peak on the (110) plane specific to the β phase (BCC), suggesting a predominantly cubic microstructure, which is characteristic of titanium alloys stabilized with Mo, Nb and Ta elements. The presence of the α″ (113) and α″ (004) peaks indicates orthorhombic α″ martensite, an intermediate phase that can form upon rapid cooling from the β phase, especially in Mo-rich and Al-free systems. This α″ phase is important because it gives the alloys a low stiffness (low elastic modulus), a highly desirable property for implants, to avoid the stress shielding effect.

3.2. Mechanical properties of alloys

The curves presented in Figure 4 illustrate the mechanical behavior of Ti-6Al-4V and Ti15Mo7Zr15Ta5Nb alloys following nanoindentation tests, highlighting the relationship between the applied force and the depth of penetration of the penetrator into the material. These results provide essential information regarding the hardness and reduced elastic modulus of the alloys, reflecting the structural and phase differences identified previously.



Ti6Al4V Ti15Mo7Zr15Ta5Nb

Fig. 4. Mechanical behavior of Ti15Mo7Zr15Ta5Nb and Ti-6Al-4V alloys on nanoindentation tests

Table 2 presents the values obtained from microindentation tests for the Ti15Mo7Zr15Ta5Nb and Ti-6Al-4V alloys, highlighting the significant differences between the two materials in terms of elastic modulus, hardness and Poisson's ratio.

Table 2. Microindentation test results of the investigated alloys

Alloy	*Elasticity modulus (GPa)*	*Hardness (GPa)*	*Poisson's Coeficient*
Ti6Al4V	113.80	3.37-3.73	0.342
Ti15Mo7Zr15Ta5Nb	40.35	2.12	0.23

The elasticity module of the Ti15Mo7Zr15Ta5Nb alloy has an elasticity module of only 40.35 GPa, significantly lower than Ti6Al4V, which reaches a value of about 113.8 GPa. This result confirms the β-stabilized character of the newly designed alloy, as the β phase has a much smaller elastic module compared to the dominant α phase. A low elasticity module is extremely advantageous in biomedical applications, as it reduces the effect of "stress shielding" and ensures better mechanical compatibility with human bone (which has a module of approx. 10–30 GPa). The Ti6Al4V alloy has a hardness between 3.37 and 3.73 GPa, which indicates a higher mechanical resistance, but correlated with increased rigidity. In contrast, the lower hardness of the Ti15Mo7Zr15Ta5Nb (2.12 GPa) alloy is in accordance with its longer and flexible nature, which can be beneficial for implants that require increased conformability, but at the same time it must be carefully analyzed from the perspective of wear resistance.

The values for Poisson's coefficient confirm the differences in elastic behavior: 0.342 for Ti6Al4V (typical value for α+alloys), respectively 0.23 for Ti15Mo7Zr15Ta5Nb, suggesting a lower transverse deformation, specific to more rigid materials on the longitudinal direction.

Conclusions

The comparative study of the Ti6Al4V (Grade 5) and Ti15Mo7Zr15Ta5Nb alloys highlighted essential differences in the microstructure, structural composition and local mechanical behaviour, with direct implications on their performances in biomedical applications.

From a microstructural point of view, Ti6Al4V has a typical lamellar microstructure α+β, resulting from the cooling in the field β, while the Ti15Mo7Zr15Ta5Nb alloy highlights a granular microstructure dominated by the β-phase, with possible transformations α″, favoured by the rapid cooling. These differences are in full agreement with the results of the X-ray diffraction, which have confirmed the predominant presence of the α phase in Ti6Al4V and the β-phase stabilized in the new alloy, along with the α″ phase.

Microindentation tests have strengthened these observations, indicating for Ti15Mo7Zr15Ta5Nb a significantly reduced elasticity module (40.35 GPA) and a lower hardness, which makes an ideal candidate for implants that require higher biomechanical compatibility with human bone tissue. Instead, Ti6Al4V, although more rigid and tougher, continues to be a robust choice for applications that involve high mechanical requests. Therefore, the optimal choice of material must take into account the specific requirements of the application, as each alloy offers a distinct set of functional and mechanical advantages.

REFERENCES

[1] Geetha, M., Singh, A. K., Asokamani, R., & Gogia, A. K. (2009). Ti based biomaterials, the ultimate choice for orthopaedic implants–a review. *Progress in Materials Science*, 54(3), 397–425.

[2] Long, M., & Rack, H. J. (1998). Titanium alloys in total joint replacement—a materials science perspective. *Biomaterials*, 19(18), 1621–1639.

[3] Bălțatu, M. S., Vizureanu, P., Sandu, A. V., Solcan, C., Hrițcu, L. D., & Spătaru, M. C. (2023). Research progress of titanium-based alloys for medical devices. *Biomedicines*, 11(11), 2997.

[4] Savin, A., Vizureanu, P., Prevorovsky, Z., Chlada, M., Krofta, J., Bălțatu, M. S., Istrate, B., & Steigmann, R. (2018). Noninvasive evaluation of special alloys for prostheses using complementary methods. *IOP Conference Series: Materials Science and Engineering*, 374(1), 012030.

[5] Bălțatu, M. S., Vizureanu, P., Sandu, A. V., Florido-Suarez, N., Săceleanu, M. V., & Mirza-Rosca, J. C. (2021). New titanium alloys, promising materials for medical devices. *Materials*, 14(20), 5934.

[6] Zhao, D., Hashimoto, N., Tane, M., & Nakajima, H. (2010). Elastic properties and stability of Ti–Mo alloys for biomedical applications. *Acta Biomaterialia*, 6(12), 4796–4804.

[7] Banerjee, D., & Williams, J. C. (2013). Perspectives on titanium science and technology. *Acta Materialia*, 61(3), 844–879.

[8] Chen, L. J., Yang, Y., Zhou, Y. L., & Guo, X. (2019). Microstructure and mechanical properties of Ti–Mo alloys for biomedical applications. *Journal of Alloys and Compounds*, 771, 1026–1034.

[9] Zhou, Y. L., Niinomi, M., Akahori, T., Fukui, H., & Toda, H. (2012). Corrosion resistance and biocompatibility of Ti–Mo alloys for biomedical applications. *Materials Science and Engineering: C*, 32(4), 705–712.

[10] Pan, C., Chou, S., Tseng, Y., Yang, Y., Wu, C., Lan, T., … & Chang, H. (2012). Influence of different implant materials on the primary stability of orthodontic mini-implants. *The Kaohsiung Journal of Medical Sciences*, 28(12), 673–678. https://doi.org/10.1016/j.kjms.2012.04.037

[11] Cotrim-Ferreira, F., Quaglio, C., Peralta, R., Carvalho, P., & Siqueira, D. (2010). Metallographic analysis of the internal microstructure of orthodontic mini-implants. *Brazilian Oral Research*, 24(4), 438–442. https://doi.org/10.1590/s1806-83242010000400011

[12] Selvaraj, S., Tandon, A., Chandrasekaran, D., Purushothaman, D., Praveen, K., Mohan, R., … & Angrish, N. (2024). Anchorage and stability of orthodontic mini implants in relation to length and types of implants. *Cureus*. https://doi.org/10.7759/cureus.73056

[13] Asok, N. (2021). Retention of mini screws in orthodontics – A comparative in vitro study on the variables. *South European Journal of Orthodontics and Dentofacial Research*, 7(2), 38–42. https://doi.org/10.5937/sejodr7-26846

[14] Sabley, K., Shenoy, U., Banerjee, S., Akhare, P., Hazarey, A., & Karia, H. (2019). Comparative evaluation of biomechanical performance of titanium and stainless steel mini implants at different angulations in maxilla: a finite element analysis. *The Journal of Indian Orthodontic Society*, 53(3), 197–205. https://doi.org/10.1177/0301574219863527

[15] Lu, X., Feng, B., Wang, P., Ding, S., Liu, Z., Zhou, J., Yu, R. (2012). In vitro and in vivo studies of surface-structured implants for bone formation. *International Journal of Nanomedicine*, 4873. https://doi.org/10.2147/ijn.s29496

[16] Ravi, J., Duraisamy, S., Rajaram, K., Kannan, R., & Arumugam, E. (2023). Survival rate and stability of surface-treated and non-surface-treated orthodontic mini-implants: a randomized clinical trial. *Dental Press Journal of Orthodontics*, 28(2). https://doi.org/10.1590/2177-6709.28.2.e2321345.oar

[17] Du, S., Song, Y., He, Y., Wei, C., Chen, R., Guo, S., Liang, W., Lei, S., & Liu, X. (2024). Evolution of microstructure and mechanical properties of Ti-6Al-4V alloy under heat treatment and multi-axial forging. *Materials*, 17, 1060. https://doi.org/10.3390/ma17051060