Proceedings in MANUFACTURING SYSTEMS

Proceedings in Manufacturing Systems, Volume 20, Issue 2, 2025, pp. 75-80 ISSN 2067-9238

NEW INEXPENSIVE Ti–Mn–Fe ALLOYS FOR MEDICAL APPLICATIONS

Clara Mihaela SOARE[1,*], Alexandra Mihaela TUDOR[2], Julia Claudia MIRZA-ROSCA[2], Victor GEANTA[3], Ionelia VOICULESCU[4]

[1, 2)] PhD Student, Doctoral School of Industrial Engineering and Robotics, National University of Science and Technology POLITEHNICA Bucharest, Romania

[2)] Prof., PhD, Department of Mechanical Engineering, University of Las Palmas de Gran Canaria, Las Palmas, Spain

[3)] Prof., PhD, Department of Engineering and Management of Metallic Materials Obtainment, Faculty of Science and Engineering of Materials, National University of Science and Technology POLITEHNICA Bucharest, Romania

[4)] Prof., PhD, Department of Quality Engineering and Industrial Technology, Faculty of Industrial Engineering and Robotics, National University of Science and Technology POLITEHNICA Bucharest, Romania

Abstract: *The paper presents the criteria for the design, production and characterization of new low-cost Ti–Mn and Ti–Fe alloys, intended for the manufacture of biomedical devices. To obtain these low-cost alloys, a commercial alloy Ti–6Al–4V is used, resulting from mechanical processing, to which alloying elements considered biocompatible, such as Fe and Mn, are added. The addition of Mn and Fe aims at stabilizing the β phase of Ti and microstructural refinement, with the aim of improving mechanical performance, while maintaining a low elastic modulus, close to that of human bone. The alloys are obtained by vacuum arc melting under argon protection. Mn and Fe are added in the form of granules with a purity of 99.5%, obtaining the Ti–3Mn alloy, with a low Fe content, and Ti–5Fe, with a low Mn content. After melting together, using high purity raw materials (over 99.5%), the concentrations of highly toxic alloying elements, such as V and Al, are reduced. The chemical concentrations of the obtained alloys are determined by X-ray spectrometric analysis, and the examination of the obtained microstructures is performed by optical and scanning electron microscopy. It is found that the Ti–Mn and Ti–Fe alloys exhibit homogeneous lamellar microstructures of α + β phases and an improved hardness compared to commercial pure titanium or Ti–6Al–4V-type alloys. Such properties indicate a strong potential for their use in the fabrication of biomedical components, particularly orthopaedic and dental implants.*

Key words: *Ti–Mn–Fe alloys, biocompatibility, microstructure, microhardness.*

1. INTRODUCTION

Due to their special properties, such as favourable strength-to-weight ratio, good corrosion resistance and excellent biocompatibility, titanium and its alloys are currently widely used in the medical field for the manufacture of orthopaedic implants, dental devices, stents, etc. [1, 2].

Although it contains chemical elements considered toxic, such as Al and V, the Ti–6Al–4V alloy is currently widely used for various medical applications because it possesses favorable mechanical properties compared to high-purity titanium. This alloy has a higher modulus of elasticity than bone (~120 GPa), which can easily cause the bone area where it is implanted to fracture [3, 4].

To overcome these problems, new titanium alloys composed mainly of the β phase have been developed recently, containing non-toxic and cost-effective stabilizers such as Mn and Fe, [5]. Both manganese and iron are naturally present in the human body in trace amounts and act as β-phase stabilizers, refining the grain structure and improving ductility and mechanical compatibility [6, 7]. The fine microstructure provides good mechanical integrity and fatigue resistance, while the balanced α / β morphology enhances ductility and dimensional stability during use.

Recently, β-type titanium alloys have gained attention due to their lower elastic modulus and better formability compared to α + β alloys. Expensive β stabilizers such as Nb, Ta, or Mo limit large-scale use [4]. Therefore, developing low-cost β-type alloys containing Mn and Fe, which are biocompatible and naturally present in trace amounts in the human body, is important [5, 6].

Previous studies show that small additions of Mn (up to 9 wt%) and Fe (up to 5 wt%) improve ductility and strength while maintaining low toxicity [2, 8–9].

Santos et al. [10] obtained Ti–Mn alloys with different Mn concentrations. They demonstrated that the maximum tensile strength of (1046 MPa), elongation at break of 4.7% and Young's modulus value of 89 GPa were obtained for 8%Mn. Titanium alloys that possess a β-phase microstructure exhibit very high mechanical strength, have good deformability and corrosion resistance in biological environments [11].

Due the fact that the chemical elements that favour β-phase stabilization are expensive, current research has focused on replacing them with cheaper and less toxic elements, such as Fe and Mn [12–15].

[*] Corresponding author address: Splaiul Independenței 313, Sector 6, 060042, Bucharest, Romania,
Tel.: 0727556752,
e-mail addresses: *claraciucur@yahoo.com* (C. Soare).

Sjafrizal et al. [16] studied the effect of iron addition in Ti–6Al alloys obtained by powder synthesis. They demonstrated that the amount of Fe should be limited to approximately 3 wt% to reduce the formation of large pores and increase the strength/modulus ratio.

Seo et al [17] used Fe in pure titanium for grain refinement and β-phase formation. They found that a concentration of 0.15% Fe was sufficient to obtain titanium grains with an average diameter below 20 µm, but they also noted a reduction in the corrosion resistance of the alloy for higher concentrations.

Balzoni et al. [18] found that the addition of Mn and Fe powders to Ti influenced the compressive behaviour of the powder mixtures, which led to an increase in the relative density, while reducing the residual porosity. Added together, these elements caused changes in the microstructure of the titanium alloy, by reducing the grain size and forming the metastable α″ phase. The fine microstructure provides good mechanical integrity and fatigue resistance, while the balanced α/β morphology enhances ductility and dimensional stability during use.

Ding et.al [19] demonstrated that Fe has a higher segregation tendency than Al and V in Ti–6Al–4V alloy. At the same time, a grain refinement effect by inhibiting interface mobility was observed. The strengthening effect depends on the diameter of the alloying atoms, being more pronounced the larger the atomic differences.

This study presents the synthesis, microstructural characterization, and mechanical evaluation of Ti–Mn–Fe alloys fabricated by vacuum arc remelting, aiming for a balance between strength, hardness, and low elastic modulus suitable for biomedical applications. The general tendency of increasing hardness for Ti–Fe and Ti–Mn alloys can be explained by the mechanism of solid solution formation during solidification of the melt. When substitute elements are added to the titanium crystal lattice, it becomes strained and its internal energy increases. This research focuses on the development of new, inexpensive Ti–Mn and Ti–Fe alloys designed for medical applications. The goal is to create biocompatible materials that retain good mechanical strength while reducing stiffness and overall production costs. Research has shown a more consistent effect of iron on the hardness of titanium alloy compared to Mn, especially in the presence of aluminum in concentrations above 2wt%.

2. EXPERIMENTAL PROCEDURE

2.1. Alloy preparation

Two titanium-based alloys were prepared from Ti–6Al–4V machining residues collected from mechanical processing operations. Manganese was added in the form of granules (99.5% purity) to obtain the Ti–3Mn alloy, while iron was added in the same purity to obtain the Ti–5Fe alloy.

The alloys were prepared by vacuum arc remelting under argon protection in MRF ABJ 900 equipment (Allenstown, NH, USA). To ensure the desired level of chemical homogeneity, six remelting cycles were performed, with successive rotation of the ingots. After melting, ingots were water-quenched from 1050 °C to retain the metastable β phase.

Two Ti-based alloys were designed from Ti–6Al–4V chips collected from mechanical processing, having the following chemical compositions determined by X-ray spectrometry (SpectromaxX, ERAMET, SIM, UPB):

- **Ti–3Mn:** 0.018 wt.% C; 0.07 wt.% Si; 3.07 wt.% Mn; 0.10 wt.% Fe; 0.06 wt.% Al; 0.04 wt.% V; 0.72 wt.% Sn; Ti balance.
- **Ti–5Fe:** 0.026 wt.% C; 0.02 wt.% Si; 4.9 wt.% Fe; 0.06 wt.% Al; 0.07 wt.% Mn; 0.04 wt.% V; 0.78 wt.% Sn; Ti balance.

2.2. Microstructure

The samples cut from the ingots using the IsoMet 4000 precision cutting machine (Buehler, Düsseldorf, Germany) were embedded in epoxy resin, ground with SiC papers, and mirror-polished with 0.3 µm alumina suspension according to ASTM E3-11 (2017) [20]. Etching was performed using Kroll's reagent (10% HF + 30% HNO_3 + 50 mL H_2O).

Optical microscopy (Olympus GX51, Tokyo, Japan) and SEM (Inspect S, FEI, Eindhoven, The Netherlands) equipped with a Z2e EDAX AMETEC sensor) were used to characterize the alloys.

2.3. Microhardness

Microhardness tests were carried out using a Shimadzu HMV-2 tester (according to ISO 6507/ISO 4545/ASTM E384 [21]) using a 100 gf (HV0.1) load. Ten indentations were performed for each alloy, and average values were calculated.

2.4. Corrosion tests

To estimate the behavior of the new alloys in different biological environments, long-term maintenance tests (1−5 weeks) were performed in solutions such as cola, wine obtained by traditional methods or commercial wine. Before immersion, the parts were thoroughly mechanically cleaned of any type of dirt adhering to the surface (oxides, corrosion, etc.), after which they were degreased with ethyl alcohol to remove traces of oil or grease.

At the same time, the titanium alloy parts were weighed with a precision scale (+/−0.001 g) to evaluate the tendency of residue deposition on their surfaces. The maintenance temperature in the biological solutions was 25 °C. The weighing was carried out at intervals of one week, and the sample surfaces were also evaluated by optical microscopy.

3. RESULTS AND DISCUSSION

3.1. Microstructure

The optical and SEM analyses revealed that both Ti–3Mn and Ti–5Fe alloys exhibit fine and homogeneous α + β lamellar structures. The Mn and Fe additions effectively stabilized the β phase and limited grain growth, ensuring uniform stress distribution under loading (Fig. 1).

At higher magnifications, in scanning electron microscopy images, the presence of acicular phases and intermetallic phases precipitated on grain boundaries in the form of agglomerations with irregular contours can be observed (Fig. 2).

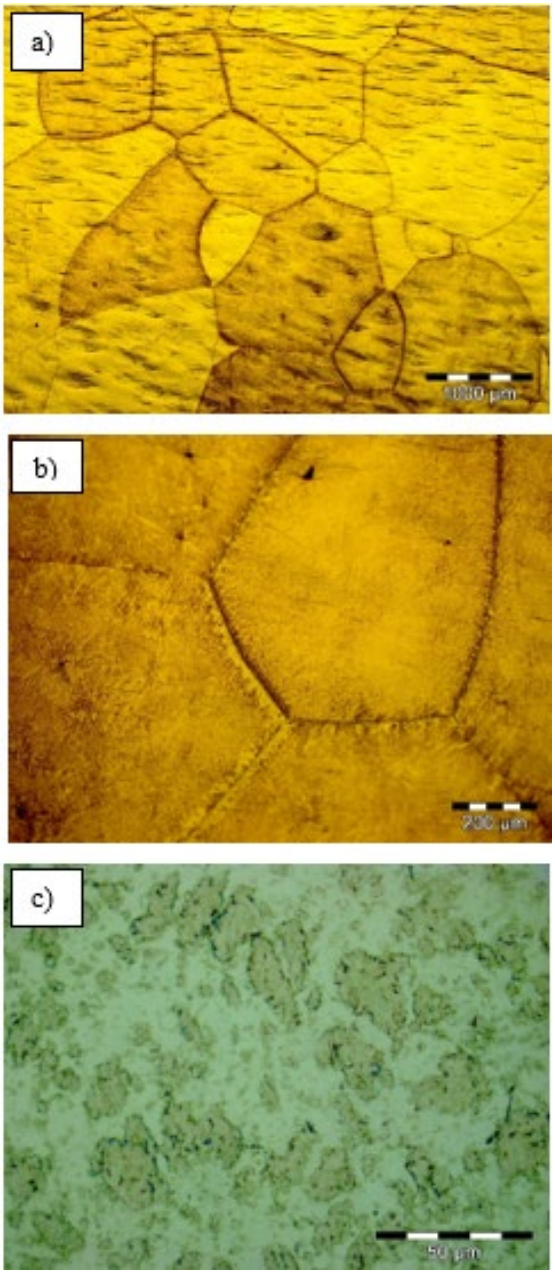

Fig. 1. Optical microstructure after Kroll etching of alloys: *a* and *b* – Ti–3Mn; *c* – Ti–5Fe.

The Ti–3Mn alloy sample contains inhomogeneous mixtures of intermetallic phases, with sizes ranging from 5 µm to 20 µm, randomly placed in the titanium metal matrix. The strengthening effect is lower than in Ti–5Fe, as dislocations lines can bypass the precipitates or only partially blocked.

As can be seen, the addition of Fe to the titanium matrix generated the appearance of intermetallic conglomerates of Fe-rich phases, with the appearance of islands with an average diameter of 20 µm. Their location at the intersection of grain boundaries allows blocking the free movement of dislocations through the grains and increasing the mechanical strength characteristics.

In the microstructure of both alloys, the presence of the acicular α/α′ phase is observed. The uniform lamellar structure suggests good microstructural control during VAR processing.

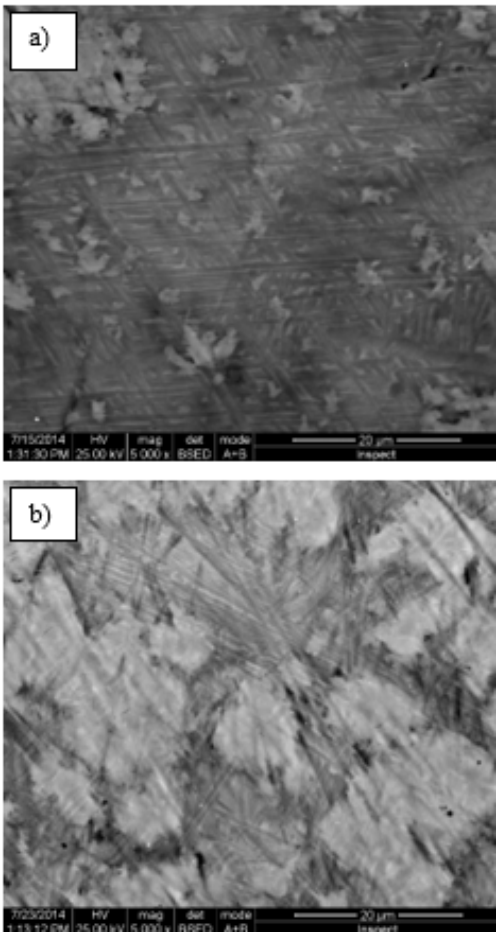

Fig. 2. SEM images alloys having acicular α/α′ structures and Fe-enriched grain boundary regions: *a* – Ti–3Mn; *b* – Ti–5Fe.

EDAX micro-zone chemical composition analysis (Fig. 3) performed on the matrix and intermetallic compounds revealed high concentrations of iron and manganese in the intergranular precipitated phases. The concentration values of the main elements (intermetallic compounds identified in Figure 2) of the analysed alloys are presented in Tables 1 and Table 2.

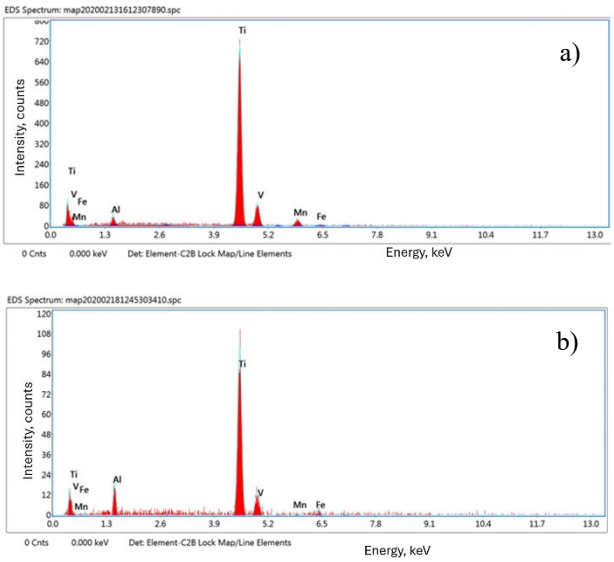

Fig. 3. Semi-quantitative composition spectra of the integrated areas in Fig. 2: *a* – Ti–3Mn; *b* – Ti–5Fe.

Table 1

Chemical elements concentration from Fig. 3,*a*

Element	Weight, %	Atomic, %	Net Int.	Error, %
Al	2.50	4.41	0.28	15.76
Ti	87.42	86.74	7.51	2.47
V	2.30	2.14	0.16	25.69
Mn	6.59	5.70	0.34	16.33
Fe	1.19	1.01	0.06	31.90

Table 2

Chemical elements concentration from Fig. 3,*b*

Element	Weight, %	Atomic, %	Net Int.	Error, %
Al	8.38	14.15	0.06	16.23
Ti	79.64	75.71	0.47	4.33
V	4.41	3.94	0.02	18.94
Mn	2.20	1.82	0.01	30.29
Fe	5.37	4.38	0.02	18.55

The relatively high concentrations of the elements Al and V in base metallic matrix coming from the raw material used in the form of span. The Fe effect in the Ti–Al alloy allows for improved casting behaviour because it reduces the liquidus temperature. In this way, the liquid-solid bi-phase range is extended to lower temperatures [22]. Studies conducted on alloys in the Ti–Fe–Al system showed that a higher concentration of Fe is obtained at the α-β phase boundaries, because it is a β-stabilizer and precipitates intergranular during cooling. Also, alloys from the Ti–Fe system possess an excellent combination of mechanical strength and ductility properties, at room temperature having strengths of up to 380 kN·m/kg and elongation at break of up to 24%.

3.2. Microhardness

The microhardness values of Ti–3Mn and Ti–5Fe alloys are presented in Fig. 4, compared to other similar alloys in the literature. According to the data presented in Fig. 3, for both alloys an increased microhardness was obtained compared to pure titanium. This strengthening effect is due to both the formation of precipitates and solid solution through the participation of Mn and Fe atoms, distorting the titanium crystal lattice and increasing the internal strain energy [4].

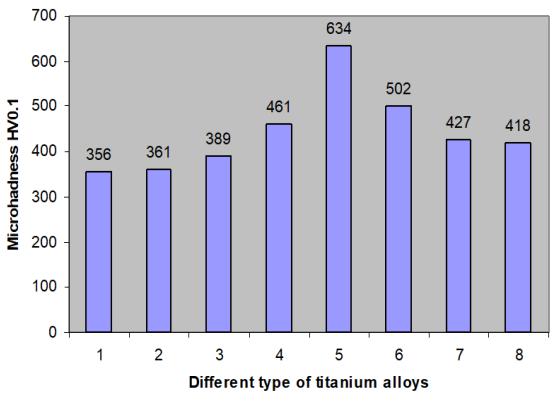

Fig. 4. Microhardness values of Ti-based alloys (1–8): 1) Ti–8A–l4V; 2) Ti–8Al–4V remelted; 3) Ti–9Al; 4) Ti–8Al–2.8Fe; 5) Ti–8Al–5Fe; 6) Ti–5Fe; 7) Ti–6Mn; 8) Ti–3Mn.

The Ti–5Fe alloy presented slightly higher hardness values than Ti–3Mn because of its higher Fe content and intermetallic formation tendency. The elastic modulus of the Ti–Mn and Ti–Fe alloys are approximately 90–95 GPa, lower than that of Ti–6Al–4V (≈120 GPa) and closer to cortical bone, thus reducing stress-shielding effects [5, 10].

Like Fe, Mn is a stabilizer of the β phase. Mn contributes to increasing the hardness of the solid solution and Fe promotes grain refinement and more uniform distribution within the metal matrix [9]. Their simultaneous presence contributes to obtaining an isotropic mechanical behaviour and the formation of a more stable structure by applying heat treatments. At the same time, such alloys benefit from a lower stiffness, compatible with the characteristic values of bone, being suitable for the manufacture of biomedical implants. These elements have mutual affinity and tend to form intermetallic compounds (like C14 Laves phase in Ti-40Fe-10Mn) by decreasing solubility upon solidification [23–24].

3.3. Corrosion behaviour

Since both Mn and Fe are naturally present in the human body, these alloys are inherently biocompatible [4]. Their use in different biological environments must also be analysed from the perspective of subsequent use for the manufacture of instruments for processing biological preparations. For this purpose, the experimental Ti–3Mn and Ti–5Fe alloys were immersed and maintained in solutions such as home wine, commercial wine, and cola (Fig. 5).

It has been demonstrated that alloys in the Ti–Mn system form double-layer passive films, which allow for increased corrosion resistance in physiological environments [9].

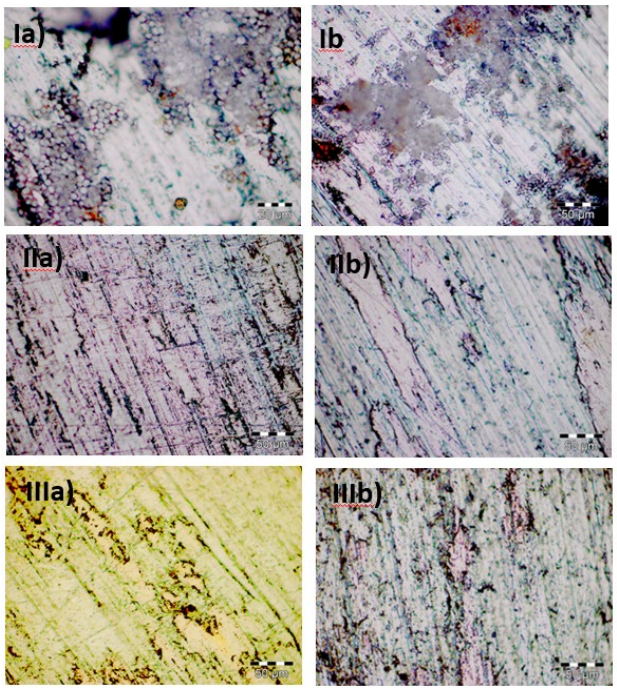

Fig. 5. Optical images of Ti–5Fe (a) and Ti–3Mn (b) after immersion in biological solutions: I – traditional wine; II – commercial wine; III – cola.

After immersion in biological solutions (traditional wine, commercial wine, and cola) for periods of 1–5 weeks at 25 °C, no significant degradation or surface deposit formation was detected on Ti–5Fe samples, whereas Ti–3Mn exhibited only minimal surface compound development. These results demonstrate good surface stability and compatibility of both alloys in environments with varying pH levels.

4. FUTURE WORK AND BIOMEDICAL APPLICATIONS

Future studies will focus on optimizing composition and heat treatment to refine the β-phase fraction and improve fatigue resistance.

Surface processing techniques require constant optimization of process parameter values to ensure the necessary depths for inducing compressive stress, reducing surface roughness, and avoiding the appearance of microcracks.

Surface engineering (e.g., anodizing or hydroxyapatite coatings, laser irradiation [25–27]) will be explored to enhance osseointegration and biological performance. It has been demonstrated that laser processing of surfaces can improve quality and engineering properties, reduce the tendency to dissolve in chemical environments, and improve behaviour in biological environments [28].

5. CONCLUSIONS

1. Ti–Mn and Ti–Fe alloys were successfully produced by vacuum arc melting using low-cost and recyclable materials.
2. Both alloys show fine α + β lamellar structures and improved hardness relative to conventional Ti alloys.
3. As a result of consolidation phenomena based on specific mechanisms, the alloys possess different hardness values, the highest hardness being recorded in the case of the Ti–5Fe alloy (502 HV0.1) compared to the Ti–3Mn alloy (418 HV0.1).
4. Regarding corrosion behaviour in commercial environments (homemade wine, commercial wine or cola), it was observed that both alloys have good resistance, with no mass loss being recorded when kept for over 5 weeks at ambient temperature. However, the Ti–3Mn alloy showed a slight tendency to form adherent surface deposits, especially in weeks 4–5, showing higher chemical reactivity and weaker corrosion stability compared to the Ti–5Fe alloy.

REFERENCES

[1] Santos, P.F.; Niinomi, M.; Cho, K. Microstructures, Mechanical Properties and Cytotoxicity of Low-Cost Beta Ti–Mn Alloys for Biomedical Applications, Acta Biomaterialia, 26 (2015), pp. 366–376.

[2] Ibrahim, P.; Garrard, R.; Penchev, P.; Man, K.; Cox, S.C.; Dimov, S.; Attallah, M.M. Hybrid Manufacturing and Performance Evaluation of β Ti-Alloy Stents. *Mater. Des.* **2024**, *247*, 113420, doi:https://doi.org/10.1016/j.matdes.2024.113420.

[3] Geanta, V.; Voiculescu, I.; Tudoran, S. Effects of Fe and Mn on Microstructure and Microhardness of Titanium Alloys, Rev. Chim., 71 (2020), pp. 87–94.

[4] Gouda, M.K.; Salman, S.A.; Ebied, S. Improvement in the Microhardness and Mechanical Behaviour of Ti–14Mn Biomedical Alloy by Cold Working, Materials Research Express, 9 (2022), 015401.

[5] Lourenço, M.L.; Cardoso, G.C.; Grandini, C.R. Development of Novel Ti–Mo–Mn Alloys for Biomedical Applications, Scientific Reports, 10 (2020), 6298.

[6] Bolzoni, L.; Yang, F.; Alshammari, Y. Titanium Alloys Developed on the Basis of the Addition of Cheap Strong β-Stabilizers, Journal of Materials Science, 58 (2023), pp. 5037–5047.

[7] Voiculescu I.; Geanta V. et al. The influence of alloying elements on the microstructure and microhardness of welded titanium alloys for medical applications, Zavarivanje i zavarene konstrukcije 64 (2019) pp.171-181, doi: 10.5937/zzk1904171V.

[8] Voiculescu, I.; Brito-Garcia, S.J.; González-Díaz, Ó.M.; Mirza-Rosca, J. Mechanical Characteristics and Corrosion Behavior of Two New Titanium Alloys. Metals 13 (2023) art.1729, https://doi.org/10.3390/ met13101729

[9] Soare, C.M.; Jimenez-Marcos, C.; Brito-Garcia, S.; Mirza-Rosca, J.C.; Voiculescu, I. Corrosion Behavior of Biocompatible Ti3Mn Alloy in Different Physiological Conditions for Biomedical Applications, Materials 18 (2025) art. 4346. doi:10.3390/ma18184346.

[10] Santos, P.F.; Niinomi, M.; Cho, K.; Nakai, M.; Liu, H.; Ohtsu, N.; Hirano, M.; Ikeda, M.; Narushima, T. Microstructures, Mechanical Properties and Cytotoxicity of Low Cost Beta Ti–Mn Alloys for Biomedical Applications. *Acta Biomater.* **2015**, *26*, 366–376, doi:10.1016/j.actbio.2015.08.015.

[11] Gouda, M.K.; Salman, S.A.; Ebied, S. Improvement in the Microhardness and Corrosion Behaviour of Ti-14Mn Biomedical Alloy by Cold Working. *Mater. Res. Express* **2022**, *9*, 015401, doi:10.1088/2053-1591/ac4b77.

[12] Nishimura, T. Effect of Microstructure on the Electrochemical Behavior of Ti-10 Mass% Mn Alloys in High Chloride Solution. *J. Mater. Eng. Perform.* **2016**, *25*, 443–450, doi:10.1007/s11665-015-1867-5.

[13] Zhou, X.; Fang, H.; Yuan, T.; Li, R. Effect of Slight Sn Modification on Mechanical Properties and Corrosion Behavior of Ti- (2–4 Wt%) Mn Alloys Fabricated via Powder Metallurgy. *Mater. Charact.* **2023**, *203*, 113068, doi:10.1016/j.matchar.2023.113068.

[14] Zhang, F.; Burkel, E. Novel Titanium Manganese Alloys and Their Macroporous Foams for Biomedical Applications Prepared by Field Assisted Sintering. In *Biomedical Engineering, Trends in Materials Science*; InTech London, UK, 2011.

[15] Zhang, F.; Weidmann, A.; Nebe, J.B.; Beck, U.; Burkel, E. Preparation, Microstructures, Mechanical Properties, and Cytocompatibility of TiMn Alloys for Biomedical Applications. *J. Biomed. Mater. Res. Part B Appl. Biomater.* **2010**, *94B*, 406–413, doi:10.1002/jbm.b.31668.

[16] Sjafrizal, T.; Dehghan-Manshadi A.; Kent, D.; Ming Yan, M.; Dargusch M. S. Effect of Fe addition on properties of Ti–6Al-xFe manufactured by blended elemental process, Journal of the Mechanical Behavior of Biomedical Materials, Volume 102, February 2020, 103518.

[17] Seo, B.; Im, H.-T.; Park, K-B.; Park, K.; Park, H-K. Effect of Iron Content on Corrosion Properties of Pure Titanium as Grain Refiner, Materials (Basel) 2021 14(23) 7193. doi:10.3390/ma14237193.

[18] Bolzoni, L.; Paul, M.; Yang, F. *et al.* Titanium alloys developed on the basis of the addition of cheap strong eutectoid β-stabilisers. *J Mater Sci* **58**, 5037–5047 (2023). https://doi.org/10.1007/s10853-023-08330-9.

[19] Ding, L.; Hu, R.; Gu, Y.; Zhou, D.; Chen, F.; Zhou, L.; Chang, H. Effect of Fe Content on the As-Cast

Microstructures of Ti–6Al–4V–xFe Alloys, *Metals* **2020**, (10) 989, doi:10.3390/met10080989.

[20] ASTM E3-11(2017); Standard Guide for Preparation of Metallographic Specimens. American Society for Testing and Materials: West Conshohocken, PA, USA, 2017.

[21] ISO 6507/ISO 4545/ASTM E384; Standard Test Method for Knoop and Vickers Hardness of Materials. International Organization for Standardization: Geneva, Switzerland, 2022.

[22] Liang Z., Miao J., Brown T., Sachdev A. K., James C. Williams J.C., Luo A.A., A low-cost and high-strength Ti-Al-Fe-based cast titanium alloy for structural applications, Scripta Materialia Vol. 157, pp.124–128, 2018.

[23] Louzguine-Luzgin D.V., High-Strength Ti-Based Alloys Containing Fe as One of the Main Alloying Elements, Materials Transactions, Vol. 59, No. 10, pp. 1537-1544, 2018.

[24] Zheng W., Song W., Wu T., Wang J., He Y., Lu X-G., Experimental investigation and thermodynamic modelling of the ternary Ti–Fe–Mn system for hydrogen storage applications, Journal of Alloys and Compounds vol. 891, art. 161957, 2021.

[25] Ahmed H., The Effect of Laser Irradiation on The Properties of Micro to Nanolayer Titanium Alloy, Journal of Materials Science Research 11(2) 2022, DOI: 10.5539/jmsr.v11n2p11.

[26] Li, J.; Su, X.; Wang, F.; Zhang, D.; Wang, Y.; Song, H.; Xu, J.; Guo, B. Effect of Laser Processing Parameters on the Quality of Titanium Alloy Cladding Layer on Carbon Fiber-Reinforced Polymer. *Polymers* 17, 1195, 2025. https://doi.org/10.3390/polym17091195.

[27] Zhechao F., Hongwei F., Study on selective laser melting and heat treatment of Ti-6Al-4V alloy, Results in Physics, Vol. 10(5), 2028, DOI: 10.1016/j.rinp.2018.07.008

[28] Liu Q., Chu S., Zhang X., Wang Y., Zhao H., Zhou B., Wang H., Wu G., Mao B., Laser shock processing of titanium alloys: A critical review on the microstructure evolution and enhanced engineering performance, Journal of Materials Science & Technology, Vol. 209, 20, pp. 262-291, 2025.