

ELECTRON BEAM TECHNIQUES FOR THE FABRICATION OF Ti-Ta COATINGS

Lyubomira Veleva^{1,2,*}, Reneta Velizarova¹, Stefan Valkov^{2,3,4}

¹*Department of Natural Sciences, University of Shumen Konstantin Preslavsky, 115
Universitetska str., 9700 Shumen, Bulgaria*

²*Institute of Electronics, Bulgarian Academy of Sciences, 72 Tsarigradsko Chaussee blvd.,
1784 Sofia, Bulgaria*

³*Technical University of Gabrovo, 4 H. Dimitar str., 5300 Gabrovo, Bulgaria*

⁴*Center of Competence “Smart Mechatronic, Eco-and Energy-Saving Systems and
Technologies”, 5300 Gabrovo, Bulgaria*

**Corresponding author: l.veleva@shu.bg*

Abstract

Titanium–tantalum (Ti–Ta) alloys combine low density, and biocompatibility of titanium with the exceptional corrosion and oxidation resistance of tantalum. In bulk form, these alloys offer high mechanical strength, good fatigue performance, low elastic modulus, and excellent resistance to aggressive environments, making them suitable for a number of biomedical and chemical applications. When applied as coatings, Ti–Ta provides protective surface layers that enhance corrosion and wear resistance, improve thermal stability, and promote strong biological integration—all without replacing the base material. This makes Ti–Ta coatings a cost-effective strategy to functionalize components for demanding environments while maintaining structural integrity. It is well known that the electron beam surface modification technique has a number of advantages in terms of the fabrication of surface structures and coatings. It enables precise, localized treatment with excellent control over depth and microstructure; improves surface properties and can refine or homogenize surface layers through rapid melting and solidification. Additionally, the process is clean, energy-efficient, and compatible with complex geometries, making it ideal for enhancing the performance of modern biomaterials. This article aims to provide a short overview on the possibilities for the fabrication of Ti-Ta coatings by the electron beam surface modification technique.

Keywords: titanium, tantalum, Ti-Ta coatings, electron beam surface modification; mechanical properties; biocompatibility.

INTRODUCTION

Titanium-based alloys are widely recognized as promising materials for modern biomedical applications due to their excellent biocompatibility, superior mechanical strength, and high corrosion resistance. They are commonly used for the fabrication of implants intended to replace damaged or failed hard tissue [1,2]. However, despite these advantages, their clinical performance may be compromised by issues such as the release of metallic ions and low values of wear resistance,

which can ultimately lead to implant failure. Since the surface of an implant plays a critical role in its interaction with the surrounding biological environment, an appropriate surface modification offers an effective solution to overcome these limitations [3-5]. In this context, titanium–tantalum (Ti–Ta) alloys have attracted increasing attention as advanced biomaterials. They combine excellent biocompatibility and corrosion resistance with a low elastic modulus that closely matches that of human bone, thereby

reducing stress shielding. Additionally, their high-temperature shape memory effect provides unique functional advantages. These characteristics make Ti-Ta alloys highly suitable for next-generation implant manufacturing. They offer improved performance, durability, and integration with host tissue, especially in the form of surface structures and coatings [6].

Currently, the methods of electron beam surface modification are considered very promising for the fabrication of surface alloys and coatings. By directing a high-energy electron beam onto the substrate, the surface layer rapidly melted, allowing the incorporation of alloying elements to form a homogeneous modified layer. The extremely fast heating and cooling rates result in fine microstructures, improved element distribution, and strong metallurgical bonding between the coating and substrate. This method offers several advantages, including precise control of the modified zone, minimal thermal distortion of the bulk material, and the ability to enhance surface properties such as hardness, wear resistance, and corrosion resistance [7-10].

The present article aims to provide a short overview of the potential of electron beam surface modification technology for the fabrication of Ti-Ta surface alloys and coatings. The discussion focuses on the influence of processing parameters on the resulting microstructure and corresponding functional properties, emphasizing how precise control of technological conditions can be used to optimize surface performance for advanced biomedical and engineering applications.

INFLUENCE OF BEAM POWER ON STRUCTURE AND PROPERTIES OF TITANIUM-TANTALUM SURFACE ALLOYS

Here, the influence of the power of the electron beam on the structure and Young's modulus of the formed Ti-Ta layers is presented [11]. The surface alloys were fabricated through electron beam surface

modification. Tantalum films with a thickness of 2.5 μm were first deposited onto pure α -Ti substrates using direct current (DC) magnetron sputtering. The deposition was carried out at a discharge voltage of 440 V and a discharge current of 1 A for 1 hour. Following this procedure, the samples were subjected to surface alloying using a continuous electron beam. During this process, the accelerating voltage was set to 50 kV, while the electron beam current varied at 15, 25, and 35 mA, corresponding to beam powers of 750, 1250, and 1750 W, respectively. The speed of the movement of the samples was maintained at 5 mm/s, and the electron beam scanning frequency was fixed at 200 Hz. A schematic representation of the electron beam surface alloying process is shown in Figure 1.

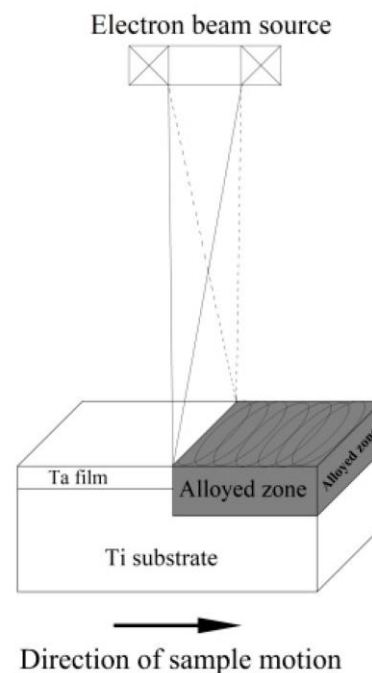


Fig. 1. Experimental scheme for the fabrication of Ti-Ta coatings by an electron beam modification [11].

The microstructure of the obtained Ti-Ta surface structures was studied by a scanning electron microscope (SEM) Figure 2a shows the cross-sectional SEM image of the sample processed at 750 W. Energy-dispersive X-ray spectroscopy

(EDS) analysis (Figures 2b,c) indicates that the Ta film remained unmelted, and no Ti–Ta surface alloy was formed, showing that the discussed value of the beam power is insufficient to dissolve Ta into the Ti substrate.

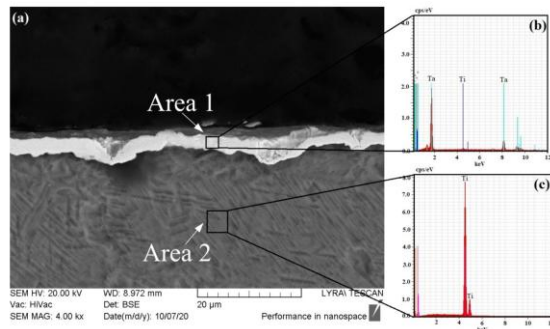


Fig. 2. A cross-sectional SEM image of the specimen modified with 750 W (a) and EDS spectra taken from different areas (b,c) [11].

At 1250 W (Figure 3a), a distinct alloyed zone (~20 μm , zone A) formed above the Ti substrate (zone B). EDS results (Figures 3b, c) show a Ti–20 wt.% Ta composition, as well as some unmelted Ta particles remained. The higher beam power increased the surface temperature, enabling partial melting and mixing due to the high-temperature gradient available in the molten zone [12]. However, complete homogenization was not achieved.

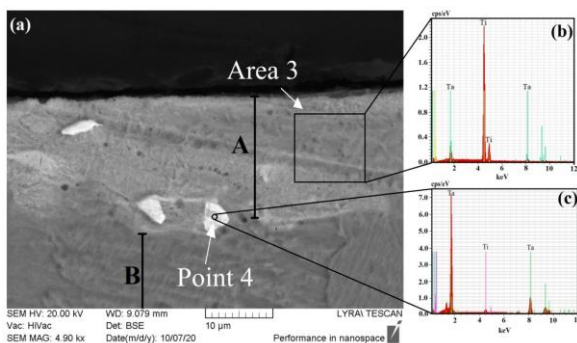


Fig. 3. A cross-sectional SEM image of the specimen modified with 1250 W (a) and EDS spectra taken from different areas (b,c) [11].

At 1750 W (Figure 4a), a thicker alloyed zone (~90 μm) formed with no undissolved Ta. EDS analysis (Figure 4b) shows a Ti–8 wt.% Ta composition. The higher power

enhanced melting, high-temperature convection, and homogeneity, while the lower Ta content is due to distribution over a thicker layer and possible evaporation. These results demonstrate that beam power strongly influences melt pool behavior, alloy thickness, and composition [13].

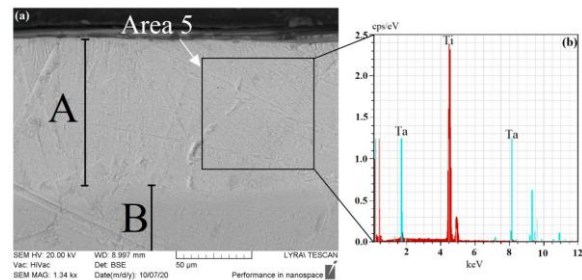


Fig. 4. A cross-sectional SEM image of the specimen modified with 1750 W (a) and EDS spectra taken from the obtained Ti-Ta coating (b) [11].

The Young's modulus of the Ti–Ta surface alloys and the base Ti substrate was evaluated. For alloys produced at beam powers of 1250 W and 1750 W, the measured values were 60.3 ± 5.1 GPa and 59.1 ± 16.2 GPa, respectively—approximately half that of the base Ti substrate (110 ± 9.8 GPa) and much closer to that of human bone. The reduction in modulus for the 1250 W alloy is attributed to the higher Ta content, which promotes the formation of the β phase, known for its lower elastic modulus. In the 1750 W alloy, the decrease is primarily due to an increase in the unit-cell volumes of the α' and β phases, which weakens atomic bonding and lowers the modulus. These findings demonstrate that electron-beam surface alloying can effectively tailor the mechanical properties of Ti–Ta alloys to better match those of natural bone.

From a practical standpoint, the substantial reduction in Young's modulus achieved for the Ti–Ta surface alloys present a clear advantage for biomedical applications, particularly in implant manufacturing. The measured values of 60.3 ± 5.1 GPa (1250 W) and 59.1 ± 16.2

GPa (1750 W) are nearly half that of pure Ti (110 GPa) and closely approach the elastic modulus of human bone (9–28.4 GPa). This improved mechanical compatibility can minimize stress shielding effects and enhance long-term implant integration and performance. These results demonstrate that Ti–Ta surface alloys produced via electron-beam alloying are promising candidates for the development of advanced biomedical implants with optimized mechanical properties [14].

INFLUENCE OF TANTALUM AMOUNT ON STRUCTURE AND PROPERTIES OF TITANIUM-TANTALUM SURFACE ALLOYS

Here, the influence of the amount of Ta alloying element on the structure and properties is presented. A 2.5 μm thick Ta film was deposited onto a pure Ti substrate via direct current (DC) magnetron sputtering. The sample underwent electron-beam treatment. The process parameters were an accelerating voltage of 50 kV, a beam current of 30 mA, a specimen translation speed of 5 mm/s, and a scanning frequency of 200 Hz. After the initial Ti–Ta layer was formed, a second Ta film with the same thickness (2.5 μm) was deposited and subjected to a second electron-beam treatment. This deposition–alloying cycle was repeated a third time to further build up the coating [15].

The phase composition after each technological cycle was studied by X-ray diffraction experiments. The experimentally obtained diffraction patterns are presented in Figure 5. Figure 5a shows the pattern corresponding to the first cycle; figure 5b presents the diffractogram of the coating fabricated by the second cycle; figure 5c – to the sample formed by the third one.

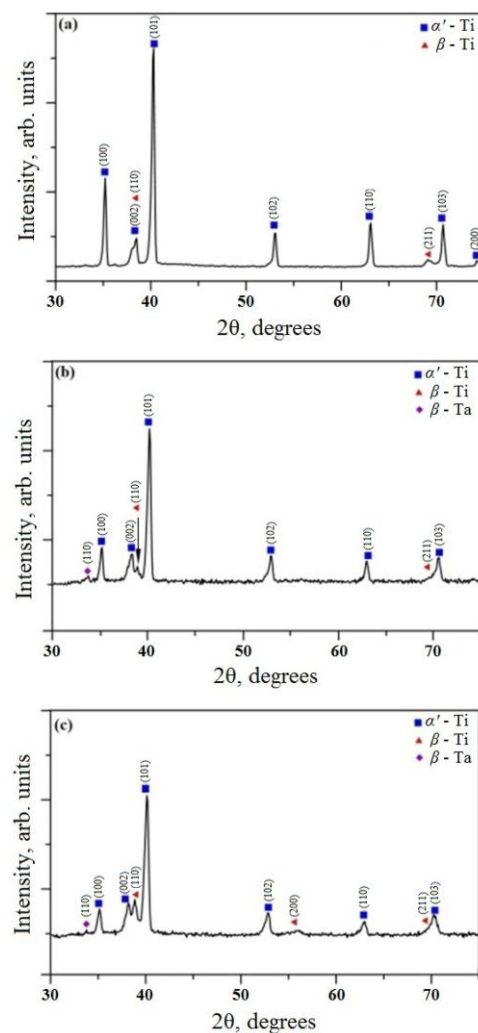


Fig. 5. Experimentally obtained diffractograms of the specimens obtained after the (a) first cycle; (b) second cycle; and (c) third cycle [15].

All patterns exhibit peaks of the α' martensitic and β phases. The α' phase possesses a hexagonal close-packed (HCP) structure, while the β phase has a body-centered cubic (BCC) structure and represents the high-temperature modification of titanium. However, the existence of the beta phase in this case is due to the incorporation of some amount of Ta element, which is known as beta stabilizer. The formation of this martensitic phase is typical for titanium-based $\alpha + \beta$ alloys subjected to high-energy treatments, such as electron-beam or laser processing.

The extremely rapid cooling rates achieved in these processes—on the order of 10^5 K/s during continuous electron-beam treatment—favor the formation of non-equilibrium phases, including metastable α' martensite [7]. Furthermore, the XRD patterns of the coatings produced in the second and third cycles show a small peak around $2\theta \approx 34^\circ$, attributed to β -tantalum. Tantalum exists in two allotropic forms, α and β , with the β phase being metastable. However, as reported in [16], β -tantalum can be stabilized in thin films and coatings. This observation is consistent with the deposition of Ta as a thin film in the present study, confirming the presence of β -Ta within the alloyed zone.

The measured Young's modulus of the pure Ti substrate was approximately 110 GPa and decreased progressively with each technological cycle of electron-beam alloying: to ~ 65 GPa after the first cycle, ~ 8 GPa after the second, and ~ 3 GPa following the third cycle. This trend indicates that increasing the Ta concentration within the alloyed zone leads to a significant reduction in Young's modulus. The phase composition of the coating plays a key role in determining its mechanical properties. In titanium alloys, the β phase exhibits the lowest Young's modulus compared to other Ti-based phases, including α -Ti and α'/α'' structures. In the present study, each cycle increased the Ta content, promoting the formation of a larger fraction of the β phase, which contributes to the observed reduction in modulus of elasticity. Also, the addition of Ta during each cycle can alter atomic distances and bonding forces. Quantitative evaluation of the α' phase unit-cell volumes from XRD data were carried out by the authors of [15] and the results revealed an increase in the HCP lattice volume with each cycle. According to [17], electron-beam surface treatment tends to expand lattice parameters and unit-cell volumes, which is consistent with these results. The increased atomic spacing weakens interatomic bonds, further reducing Young's modulus.

Once again, it is important to note that the reported reduction in Young's modulus achieved for the Ti-Ta surface alloys present a clear advantage for biomedical applications, particularly in implant manufacturing. The measured values of about 3 GPa are significantly lower than that of pure Ti (110 GPa) and almost match the elastic modulus of human bone (9–28.4 GPa). This improved mechanical compatibility can minimize stress shielding effects and enhance long-term implant integration and performance. These results demonstrate that Ti-Ta surface alloys produced via selective electron-beam alloying are promising candidates for the development of advanced biomedical implants with optimized mechanical properties.

CONCLUSION

In conclusion, electron beam technologies represent an effective and versatile approach for the fabrication of Ti-Ta surface alloys. The high energy density and precise controllability of the process enable localized melting and thorough mixing of titanium substrate and tantalum alloying element, resulting in a homogeneous surface alloy. The rapid solidification associated with this technique promotes the formation of metastable phases, while minimizing thermal effects on the bulk material. Moreover, the vacuum environment ensures high coating purity, and the layer-by-layer processing allows precise tailoring of the alloy's composition and microstructure. These advantages make electron beam processing particularly well suited for producing high-performance Ti-Ta surface alloys for advanced engineering and biomedical applications.

Acknowledgments: This research was funded by the University of Shumen Konstantin Preslavsky, grant number RD-08-113/05.02.2025. The electron beam surface modification experiments were performed thanks to the lab equipment of

the Operational Program “Scientific Research, Innovation and Digitization for Smart Transformation 2021–2027”, Project CoC “Smart Mechatronics, Eco- and Energy Saving Systems and Technologies”, BG16RFPR002-1.014-0005.

REFERENCE

- [1] Jia, M.; Zhang, D.; Liang, J.; Gabbitas, B. Porosity, Microstructure, and Mechanical Properties of Ti-6Al-4V Alloy Parts Fabricated by Powder Compact Forging. *Metall. Mater. Trans.* 2017, 48, 2015–2029.
- [2] Elias, C.; Lima, J.; Valiev, R.; Meyers, M. Biomedical applications of titanium and its alloys. *JOM* 2008, 60, 46–49.
- [3] Valkov, S.; Parshorov, S.; Andreeva, A.; Bezdushnyi, R.; Nikolova, M.; Dechev, D.; Ivanov, N.; Petrov, P. Influence of Electron Beam Treatment of Co–Cr Alloy on the Growing Mechanism, Surface Topography, and Mechanical Properties of Deposited TiN/TiO₂ Coatings. *Coatings* 2019, 9, 513.
- [4] Wooley, P.; Schwarz, E. Aseptic loosening. *Gene Ther.* 2004, 11, 402–407.
- [5] Kelly, P.; Arnell, R. Magnetron sputtering: A review of recent developments and applications. *Vacuum* 2000, 56, 159–172.
- [6] Song, Y.; Xu, D.; Yang, R.; Li, D.; Wu, W.; Guo, Z. Theoretical study of the effects of alloying elements on the strength and modulus of beta-type bio-titanium alloys. *Mater. Sci. Eng. A* 1999, 260, 269–274.
- [7] Valkov, S.; Ormanova, M.; Petrov, P. Electron-Beam Surface Treatment of Metals and Alloys: Techniques and Trends. *Metals* 2020, 10, 1219.
- [8] Valkov, S.; Ormanova, M.; Petrov, P. Surface manufacturing of materials by high energy fluxes. In *Advanced Surface Engineering Research*; Chowdhury, M.A., Ed.; IntechOpen: London, UK, 2018; pp. 69–87.
- [9] Valkov, S.; Petrov, P.; Lazarova, R.; Bezdushnyi, R.; Dechev, D. Formation and characterization of Al–Ti–Nb alloys by electron-beam surface alloying. *Appl. Surf. Sci.* 2016, 389, 768–774.
- [10] Petrov, P. Electron beam surface remelting and alloying of aluminium alloys. *Vacuum* 1997, 48, 49–50.
- [11] Valkov, S.; Dechev, D.; Ivanov, N.; Bezdushnyi, R.; Ormanova, M.; Petrov, P. Influence of Beam Power on Young’s Modulus and Friction Coefficient of Ti–Ta Alloys Formed by Electron-Beam Surface Alloying. *Metals* 2021, 11, 1246.
- [12] Chan, C.; Mazumder, J.; Chen, M. A two-dimensional transient model for convection in laser melted pool. *Metall. Trans. A* 1984, 15, 2175–2184.
- [13] Angelov, V.; Ormanova, M.; Kaisheva, D.; Lazarova, R.; Dimitrova, R.; Petrov, P. Selective electron beam surface alloying of aluminum with TiCN nanoparticles. *Nucl. Instrum. Methods Phys. Res. B* 2019, 440, 88–94.
- [14] Zhou, Y.; Niinomi, M.; Akahori, T. Effects of Ta content on Young’s modulus and tensile properties of binary Ti–Ta alloys for biomedical applications. *Mater. Sci. Eng. A* 2004, 371, 283–290.
- [15] Ormanova, M.; Dechev, D.; Ivanov, N.; Mihai, G.; Gospodinov, M.; Valkov, S.; Enachescu, M. Synthesis and Characterization of Ti-Ta-Shape Memory Surface Alloys Formed by the Electron-Beam Additive Technique. *Coatings* 2022, 12, 678.
- [16] Magnuson, M.; Greczynski, G.; Eriksson, F.; Hultman, L.; Höglberg, H. Electronic structure of β -Ta films from X-ray photoelectron spectroscopy and first-principles calculations. *Appl. Surf. Sci.* 2019, 470, 607–612.
- [17] Bouscaud, D.; Pesci, R.; Berveiller, S.; Patoor, E. Estimation of the electron beam-induced specimen heating and the emitted X-rays spatial resolution by Kossel microdiffraction in a scanning electron microscope. *Ultramicroscopy* 2012, 115, 115–119.