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TAILORING THE STRUCTURE AND FUNCTIONAL PROPERTIES OF TITANIUM-BASED THIN FILMS THROUGH CONTROLLED DEPOSITION PARAMETERS FOR MECHANICAL AND BIOMEDICAL APPLICATIONS

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Ti-Au thin film/coating, magnetron sputtering (PVD), surface morphology, mechanical properties, hardness, surface roughness, friction coefficient.

ABSTRACT
This study examines the structure and surface characteristics of Ti–Au thin films and coatings deposited by the PVD magnetron sputtering method in a vacuum/argon/nitrogen environment at an elevated temperature of 450 °C using direct-current and radio-frequency sputtering modes. Based on a series of experimental investigations aimed at determining the optimal deposition conditions, the synthesized thin films and coatings were designated as follows: Ti–Au (TR-1), Ti–Au–Ag (TR-2), (Ti–Au–Ag)N (TR-3), Ti–Au–Cu (TR-4), and (Ti–Au–Cu)N (TR-5). The NanoPVD system was utilized to deposit coatings with a consistent mean thickness of roughly 1 μm. Experimental data indicate that the coatings' chemical makeup, microstructure, and functional behavior are highly sensitive to magnetron sputtering parameters. The influence of Ag and Cu doping on the mechanical and microstructural properties of Ti–Au films was analyzed via SEM/EDX and XRD. Furthermore, AFM was employed to assess surface roughness, while nanoindentation and tribological testing provided a thorough evaluation of mechanical performance. Findings confirm that PVD-based surface modification of Ti_6Al_4V substrates substantially improves wear resistance and lowers friction coefficients. XRD analysis suggests that these enhanced tribological properties are primarily linked to the development and increased volume fraction of the Ti_3Au (β) phase.

INTRODUCTION

In recent decades, the field of biomedical materials, particularly the development of biocompatible and wear-resistant advanced coatings for medical implants and surgical instruments, has experienced significant technological progress (Wilches L.V. et al. 2008, Rahmati B. et al. 2016, Panjwani B. et al. 2011, Guan J. et al. 2021 and Wei M. et. al. 2021). Research in this area is primarily focused on improving the long-term reliability and stability of surface coatings under prolonged physiological conditions. Among the most promising directions in biomedical materials science, particular attention has been devoted to thin-film coatings based on titanium (Ti) and its alloys (Mu J. et al. 2021, Wang Y.H. et al. 2022, Özkan D. et al. 2021, Çomaklı O. et al. 2023 and Bai H. et al. 2021). This interest is attributed to their excellent corrosion resistance,

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outstanding biocompatibility, and favorable physical-mechanical properties, including high hardness, density, and strong adhesion to the substrate (Lopes C. et al. 2015 and Łępicka M. et al. 2019). Furthermore, the functional performance of these coatings—including wear resistance, friction coefficient, surface energy, and antibacterial activity—can be significantly enhanced through optimization of their chemical composition, micro- and nanostructure, as well as deposition parameters (Birkett M. et al. 2013, Ruggiero A. et al. 2015 and Ait-Djafer A.Z. et al. 2015). These approaches improve the practical performance of the coatings and broaden their potential applications in biomedical engineering.

In this context, Ti–Au alloys, particularly the Ti–Au intermetallic system, have attracted considerable attention because of their exceptional combination of biocompatibility and mechanical hardness. Recent studies have demonstrated that Ti–Au alloys exhibit superior mechanical strength, making them promising candidates for protective coatings on biomedical implants. Moreover, the incorporation of Ag (silver) and Cu (copper) into the Ti–Au matrix not only imparts antibacterial properties but also enhances the wear resistance of the coatings. This strategy, combining improved tribological performance with antimicrobial functionality, represents a promising approach for extending the service life of medical devices while reducing the risk of implant-associated infections.

Among the various thin-film deposition techniques, Physical Vapor Deposition (PVD) magnetron sputtering has proven to be one of the most effective methods for fabricating high-quality coatings because it provides precise control over coating composition, microstructure, thickness, and surface morphology. In particular, the use of multicomponent targets together with optimized deposition parameters enables tailoring of the phase composition and morphological characteristics of the coatings to satisfy specific biomedical requirements (Lukose C.C. et al. 2022, Villapún V.M. et al. 2018, Chavignon C. et al. 2022, Birkett M. et al. 2022, Lukose C.C. et al. 2023, Macías H.A. et al. 2018, Baptista A. et al. 2018, Palmero A. et al. 2021, Yumusak G. et al. 2020, Yumusak G. et al. 2022, Thampi V.A. et al. 2016, Wojcieszak D. et al. 2020, Stranak V. et al. 2014 and Karimi A. et al. 2018).

The present study is devoted to a comprehensive investigation of Ti–Au-based thin-film coatings deposited using the NanoPVD system, an advanced magnetron sputtering platform, as well as modified coating systems obtained by incorporating Ag and Cu into the Ti–Au matrix. The primary objective of this work is to systematically evaluate the microstructural characteristics, physical-mechanical properties—including hardness, wear resistance, and coefficient of friction—and the electrochemical corrosion resistance of the synthesized coatings. Furthermore, the potential application of these coatings as surface modifications for biomedical implants and as functional engineering coatings is assessed. The findings of this study provide valuable insights into the relationships between composition, microstructure, and performance, highlighting the potential of Ti–Au-based coatings for biomedical applications requiring enhanced biocompatibility, corrosion resistance, and controlled surface morphology.

MATERIALS AND METHODS

In the present study, an advanced NanoPVD magnetron sputtering technique was employed as the deposition method, providing precise control of the chemical composition and enabling the formation of uniform, dense thin-film coatings over a large substrate area. Ti–AuX (X = Ag, Cu) thin-film coatings were deposited by Physical Vapor Deposition (PVD) magnetron sputtering onto laboratory glass substrates and medical-grade Ti_6Al_4V alloy substrates.

The coatings were synthesized using a NanoPVD-S10A magnetron sputtering system (Moorefield Nanotechnology Ltd., UK) (see Figure 1). Ti_6Al_4V substrates with dimensions of 76 × 25 × 1 mm^3 were mechanically polished using a polishing machine equipped with SiC abrasive papers ranging from P240 to P4000 grit until a smooth surface with a roughness of less than 40

nm was achieved. Surface roughness in different directions was monitored using an Alicona Infinite Focus optical measurement system.

After polishing, the Ti_6Al_4V substrates were sectioned into specimens measuring 19×25 mm². The specimens and standard glass substrates (76×25×1 mm³) underwent a cleaning process involving a 5:1 Decon 90/water solution, assisted by ultrasonication. To eliminate surface impurities, the substrates were rinsed sequentially with isopropyl alcohol (IPA) and acetone. After drying with high-purity nitrogen, they were positioned 100 mm from the plasma source within the sputtering chamber. To achieve a uniform coating, the substrate holder was rotated at a constant speed of 5 rpm throughout the deposition process.

Thin-film coatings were deposited using two symmetrically positioned magnetron cathodes operating in a co-sputtering configuration, which enabled the formation of intermetallic compounds through the simultaneous sputtering of two different target materials. For co-deposition, Ti and Au targets (50.8 mm in diameter and 6.35 mm in thickness) were installed in separate magnetron sources. The Ti mosaic target was operated under DC power, while RF excitation was applied to the Au target.

To introduce Ag and Cu into the Ti–Au coatings during deposition, the Ti mosaic target was modified with eight cylindrical recesses (3 mm in diameter and 4 mm deep) on its sputtering surface. These recesses accommodated Ag or Cu inserts, allowing the alloying elements to be incorporated directly during the sputtering process.

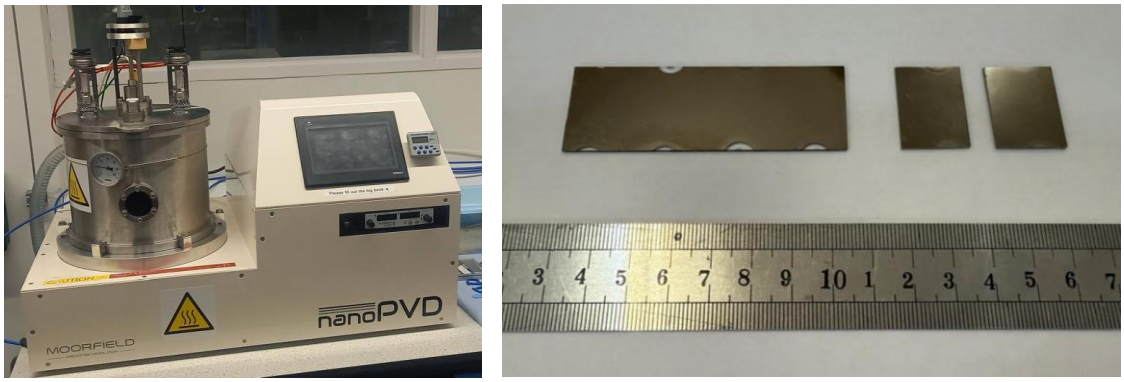


Figure 1. NanoPVD-S10A magnetron sputtering system and Ti–Au coatings deposited on different substrates (laboratory glass and Ti_6Al_4V alloy)

Note – compiled by the authors

To investigate the chemical composition and surface morphology of the Ti–Au-based thin-film coatings deposited by the NanoPVD process, energy-dispersive X-ray spectroscopy (EDS) coupled with scanning electron microscopy (SEM) was employed. The analyses were performed using Scios 2 (Thermo Scientific) and TESCAN VEGA scanning electron microscopes operated at accelerating voltages ranging from 10 to 15 kV (see Figure 2). The crystalline structure of the deposited coatings was characterized by X-ray diffraction (XRD). Diffraction measurements were carried out using a D8 VENTURE diffractometer (Bruker) and a MiniFlex II benchtop diffractometer (Rigaku). The measurements were performed at an operating voltage of 40 kV and a tube current of 40 mA using Cu Kα radiation (λ = 1.5418 Å). Diffraction patterns were recorded with a step size of 0.05°, a counting time of 0.2 s per step, and a 2θ scanning range from 20° to 90° (see Figure 3).

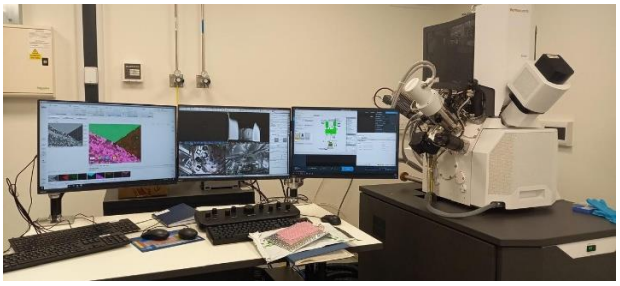


Figure 2. Scanning electron microscope (SEM) Scios 2 (Thermo Fisher Scientific)
Note – compiled by the authors



Figure 3. Photograph of the D8 VENTURE X-ray diffractometer (XRD) (Bruker)
Note – compiled by the authors

For a detailed investigation of the surface morphology of the coatings at the nanoscale, atomic force microscopy (AFM) was employed (see Figure 4). The analyses were performed on the coatings in the as-deposited condition following plasma cleaning. All measurements were carried out in tapping mode, and at least three different surface areas were scanned for each specimen to ensure the reproducibility of the results. The nanohardness of the deposited coatings was determined using a FISCHERSCOPE HM2000 S nanoindentation system.

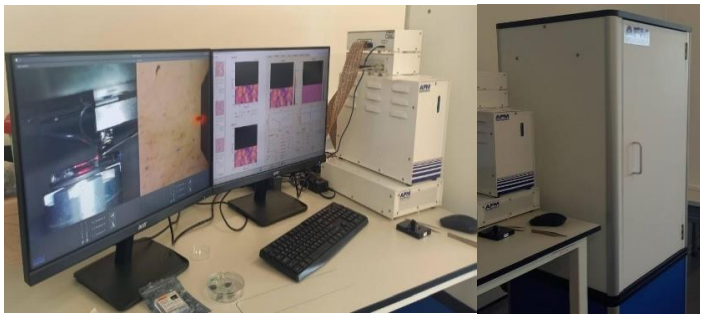


Figure 4. Photograph of the AFM Workshop atomic force microscope (AFM)
Note – compiled by the authors

The coefficient of friction of the Ti–Au-based coatings was determined by ball-on-disc tribological tests using a Tribometer TRB3 (Anton Paar). The experiments were carried out under ambient laboratory conditions at a temperature of 26.14 °C and a relative humidity of 71.44%. Prior to testing, the surfaces of all specimens were thoroughly cleaned with ethanol (C_2H_5OH) to

remove surface contaminants. A certified 6 mm 100Cr6 steel ball served as the counterbody in the tribological experiments. Tests were carried out at a normal load of 1 N and a sliding velocity of 1 cm s^{-1} using a 2.5 mm track radius, with the sliding distance fixed at 70 m. The testing protocol complied with ASTM G133-95 and ASTM G99 standards.

RESULTS AND DISCUSSION

The optimized deposition conditions, coating parameters, and technological characteristics of the fabricated samples are summarized in Table 1. During the deposition process, the required Ti:Au stoichiometric ratio of 3:1 was strictly maintained. To achieve this composition, the power supplied to each magnetron—DC power for the Ti target and RF power for the Au target—was precisely controlled throughout the deposition process. The coatings were deposited in an argon (Ar) atmosphere, while the nitrogen (N_2) partial pressure was varied between 0 and 0.8 Pa, depending on the deposition conditions. Prior to coating deposition, the substrates were heated to 450 °C, which promoted improved adhesion between the thin film and the substrate and facilitated the formation of a well-developed crystalline structure.

Table 1. Deposition parameters and technological characteristics used for the fabrication of Ti–Au-based thin-film coatings by the NanoPVD process

Sample No.	Coating Material	Ar Flow Rate (cm^3/min)	N_2 Flow Rate (cm^3/min) (Pa)	Substrate Temperature During Deposition (°C)	Deposition Time (s)
1 (TR-1)	Ti-Au	5	0	450	3000
2 (TR-2)	Ti-Au-Ag	5	0		
3 (TR-3)	Ti-Au-Ag	5	0.7		
4 (TR-4)	Ti-Au-Cu	5	0		
5 (TR-5)	Ti-Au-Cu	5	0.8		
Note – compiled by the authors					

According to data from scanning electron microscopy (SEM), the synthesis of titanium-gold (Ti-Au) thin-film coatings using the PVD method exhibits certain characteristics in the formation of surface morphology. Figure 5 shows an SEM image of the surface of Ti-Au-based thin-film coatings produced using the NanoPVD-S10A magnetron system. The coatings exhibit a microstructure characteristic of vacuum-based deposition techniques, namely high density, compositional homogeneity, and a relatively thin coating layer. The deposited surface is characterized by a well-defined and highly ordered microstructure with a uniform distribution of the constituent elements. It is well established that pure titanium coatings deposited by PVD typically consist of well-oriented grains with a triangular-pyramidal morphology (Lukose C.C. et al. 2022 and Wojcieszak D. et al. 2020). In contrast, the Ti–Au thin films synthesized in the present study exhibit a dense microstructure composed predominantly of dome-shaped grains (Figure 5a). The SEM observations further reveal that the incorporation of small amounts of Ag and Cu (Figures 5b and 5c, respectively) results in the formation of bright features uniformly distributed throughout the gray Ti–Au matrix. In the Ag-containing coating, these features appear as well-defined faceted polyhedral grains (Figure 5b), whereas the Cu-containing coating is characterized by the formation of spherical grains (Figure 5c). Similar faceted-to-rounded grain morphologies have previously been reported for Ti-based coatings alloyed with Cu (Stranak V. et al. 2014 and Karimi A. et al. 2018). The Ti–Au-based coatings additionally deposited in a nitrogen (N_2) atmosphere are not presented in this study. These coatings exhibited significant refinement of the primary matrix grains, resulting in a nanocrystalline microstructure.

Furthermore, the formation of nitrogen-containing compounds produced characteristic artifacts in the SEM analysis, complicating the accurate interpretation of the micrographs.

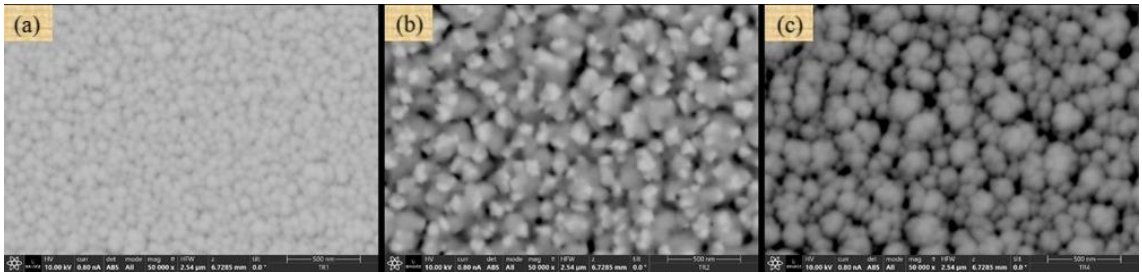


Figure 5. SEM micrographs of the surface morphology of Ti–Au-based thin-film coatings: (a) pure Ti–Au; (b) Ti–Au alloyed with silver (Ag); and (c) Ti–Au alloyed with copper (Cu)
Note – compiled by the authors

To characterize the chemical composition of the Ti–Au-based coatings, elemental analysis was performed using energy-dispersive X-ray spectroscopy (EDX). Measurements were carried out at five different locations on the coating surface, and the reported results represent the average values obtained from these measurements. The elemental composition is presented as a histogram (Figure 6) and summarized in Table 2. In addition, EDX analysis was performed on the cross-sections of the coatings, covering the entire region highlighted in green in the corresponding image. The cross-sectional analysis revealed that titanium (Ti) and gold (Au) are distributed relatively uniformly throughout the thickness of the coatings in all samples (see Figure 7).

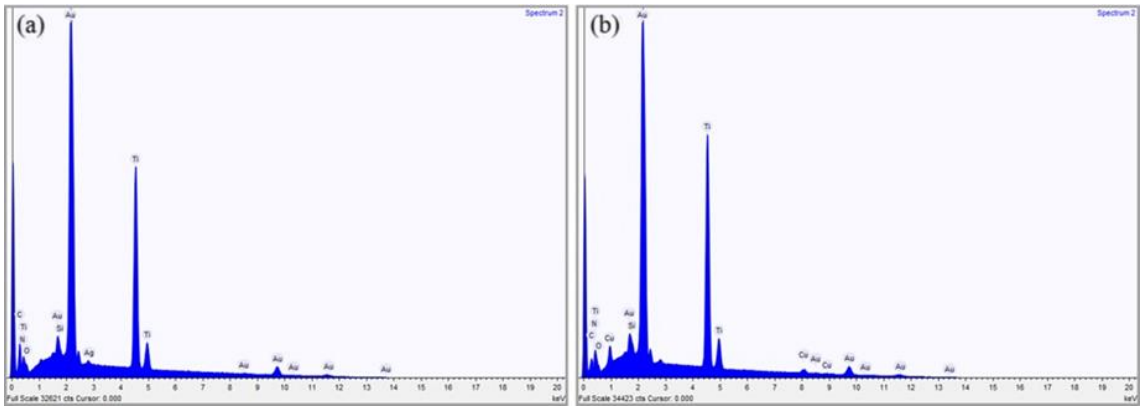


Figure 6. SEM/EDX images of Ti–Au coatings processed in a nitrogen (N_2) atmosphere: (a) with silver (Ag) addition and (b) with copper (Cu) addition (elemental analysis was performed on the coating surface)
Note – compiled by the authors

It was demonstrated that the physicochemical interactions occurring within the vacuum chamber during ion sputtering in a nitrogen (N_2) atmosphere promote the uniform incorporation of Ag and Cu throughout the entire coating volume. These results confirm that nitrogen (N_2) modification is an effective approach for optimizing the distribution of alloying elements within the coating.

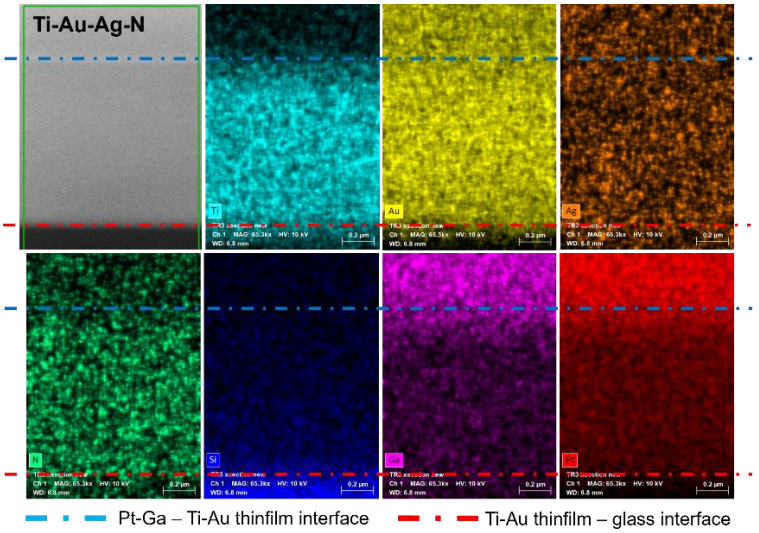


Figure 7. Cross-sectional EDX analysis of the Ti–Au-based coating alloyed with Ag and processed in a nitrogen (N_2) atmosphere

Note – compiled by the authors

According to the results of the elemental analysis, the presence of oxygen (O) and silicon (Si) in the obtained spectra is primarily attributed to the composition of the laboratory substrates used for the EDX measurements. Specifically, these elements originate from the glass substrates composed of silicon dioxide (SiO_2). Furthermore, during the preparation of cross-sectional specimens using focused ion beam–scanning electron microscopy (FIB–SEM), gallium (Ga) and platinum (Pt) were detected on the coating surface. These elements were intentionally introduced as part of a temporary Ga–Pt protective conductive layer, which was deposited to facilitate precise localization of the milling region and to protect the coating from ion-beam-induced damage during FIB processing. This approach is widely employed in modern microstructural characterization.

Table 2. Elemental composition of Ti–Au-based coatings determined by SEM/EDX analysis

Sample No.	Average Thickness (nm)	EDX (at.%) – Average value from 5 measurement points and 5 different areas						Ti/Au Ratio
		Ti	Au	Ag	Cu	N	Total	
1 (TR-1)	1170	73.3	26.7	-	-	-	100	2.7
2 (TR-2)	1050	65.2	32.4	2.4	-	-	100	2.0
3 (TR-3)	1050	60.7	27.7	0.2	-	11.4	100	2.2
4 (TR-4)	1550	64.6	19.8	-	15.6	-	100	3.3
5 (TR-5)	1100	63.2	20.1	-	2.9	13.8	100	3.1
Note – compiled by the authors								

To comprehensively investigate the morphological characteristics of the coatings, additional analyses were performed using atomic force microscopy (AFM) alongside scanning electron microscopy (SEM). AFM enabled high-resolution three-dimensional visualization of the surface topography of the Ti–Au coatings, allowing the spatial morphology, micro- and nanoscale surface features, and the average surface roughness (Rq) to be quantitatively evaluated. Figure 8 presents AFM images of the Ti–Au-based thin-film coatings, illustrating the surface uniformity and the size and structural characteristics of the morphological features. The AFM analysis

demonstrated that the addition of silver (Ag) significantly influences the surface morphology of the coatings. As shown in Figure 8b, Ag incorporation promotes the formation of larger surface reliefs and well-defined polyhedral structures. These morphological changes may be attributed to the redistribution of surface energy and modifications in the crystallization process. The high-resolution AFM images confirmed the relatively homogeneous surface morphology and low surface roughness values, which are consistent with the SEM observations. The average surface roughness (Rq) values were 13.4 ± 1.0 nm for Sample 1 (Ti–Au), 17.4 ± 1.8 nm for Sample 2 (Ti–Au–Ag), 8.7 ± 2.4 nm for Sample 3 (Ti–Au–Ag–N), 13.5 ± 2.7 nm for Sample 4 (Ti–Au–Cu), and 2.3 ± 0.8 nm for Sample 5 (Ti–Au–Cu–N). These results indicate that the incorporation of Ag and Cu, as well as nitrogen (N_2) modification, has a significant influence on the surface morphology and microgeometrical characteristics of the coatings (see Table 3).

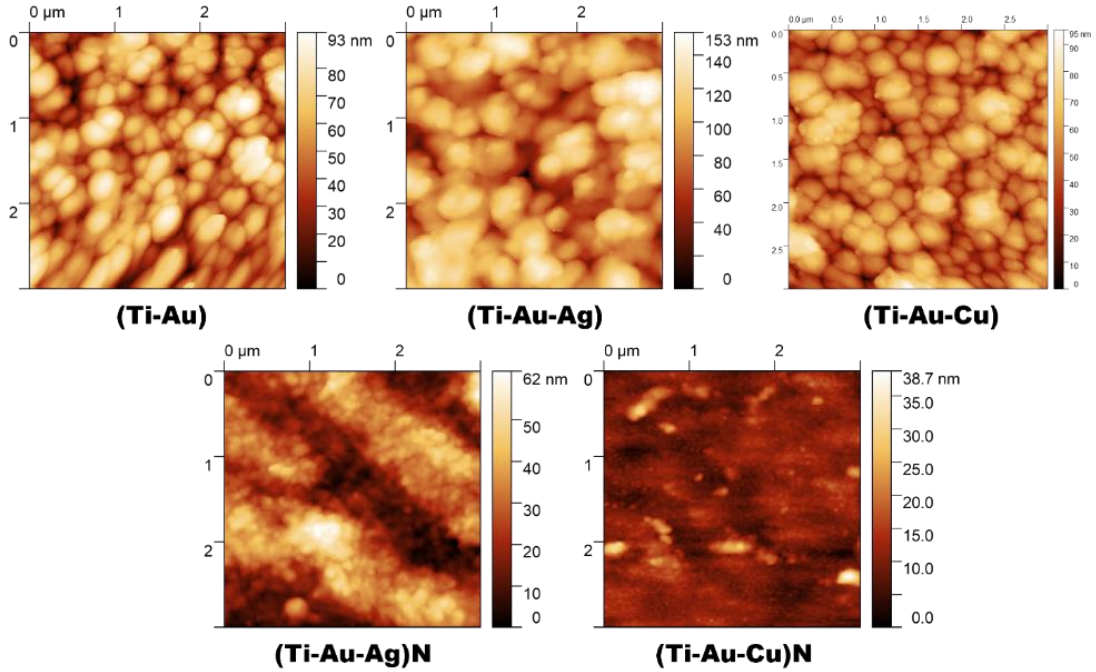


Figure 8. Two-dimensional (2D) AFM images of the coatings.
Note – compiled by the authors

Table 3. Average surface roughness (Rq) values of Ti–Au-based thin-film coatings determined by AFM analysis

Sample No.	Surface Roughness (Rq), nm	Standard Deviation (Std. Dev.), nm
1	13.4	1.0
2	17.4	1.8
3	8.7	2.4
4	13.5	2.7
5	2.3	0.8
Note – compiled by the authors		

Based on the results obtained from SEM/EDX and AFM analyses, it was established that the agglomeration of silver (Ag) and copper (Cu) particles significantly influences the structural and morphological characteristics of Ti–Au-based thin-film coatings. The tendency of Ag and Cu particles to form agglomerates can substantially affect the structural evolution of Ti–Au-based coatings. Such redistribution of the alloying elements may alter the preferred crystallographic

orientation and crystallite characteristics, while also influencing the cross-sectional morphology, coating compactness, and surface topography. These microstructural changes can, in turn, contribute to variations in the physical and mechanical performance of the coatings. Therefore, understanding the role of Ag and Cu distribution is important for establishing the relationship between alloying and the morphological stability of Ti–Au-based films.

To determine the phase composition of the deposited Ti–Au-based coatings, X-ray diffraction (XRD) analysis was performed. Since the X-ray penetration depth in XRD depends on the incident angle and is typically approximately 0.3 μm, coatings deposited on laboratory glass substrates were used to ensure reliable phase identification. This approach enables the diffraction signals originating exclusively from the coating to be recorded while minimizing contributions from the Ti_6Al_4V substrate. Furthermore, considering that the average coating thickness was approximately 1 μm (see Table 2), the use of glass substrates during XRD measurements provided more accurate phase identification without substrate-induced interference. During physical vapor deposition (PVD) at an elevated substrate temperature of approximately 450°C, a thermodynamically stable β-Ti_3Au intermetallic phase was formed. This behavior is attributed to the temperature-enhanced atomic diffusion and increased reaction kinetics between Ti and Au atoms. According to the XRD phase analysis, the Ti–Au, Ti–Au–Ag, and Ti–Au–Cu coatings predominantly consisted of the β-Ti_3Au phase (cubic crystal structure, space group Pm-3n, a = 5.09600 Å). In addition, a small fraction of the α-Ti_3Au phase (cubic crystal structure, space group Pm-3m, a = 4.14700 Å) was also detected. In contrast, the Ti–Au–Ag–N coating exhibited pronounced structural changes after nitrogen modification. The characteristic diffraction peaks corresponding to the β-Ti_3Au planes ((101), (200), (201), (211), (202), (301), (222), (230), (321), (400), (411), and (402)) disappeared and were replaced by diffraction peaks corresponding to the TiN phase (cubic crystal structure, space group Fm-3m, a = 4.10500 Å), indexed to the (111), (200), (202), (311), (222), and (400) crystallographic planes. Since TiN and AgN (cubic crystal structure, space group Fm-3m, a = 4.10900 Å) possess the same face-centered cubic crystal structure (space group No. 225), favorable crystallographic conditions are created for the incorporation of Ti, Cu, and Ag atoms into the crystal lattice. For the Ti–Au–Cu–N coating, a decrease in the fraction of the β-Ti_3Au phase accompanied by an increase in the α-Ti_3Au phase was observed. This transformation is confirmed by the diffraction peaks indexed to the (101), (200), (201), (211), (300), and (202) crystallographic planes characteristic of α-Ti_3Au (see Figure 9).

The load–displacement curves obtained from the nanoindentation tests of the Ti–Au-based samples (see Figure 10) illustrate the interaction between the diamond indenter and the surface of the thin-film coatings. For comparison, the nanoindentation responses of the Ti–Au-coated samples and the uncoated Ti_6Al_4V alloy substrate are presented. All load–displacement curves were recorded under a maximum applied load of **2000 μN**, with loading, holding, and unloading durations of 20 s each.

For the uncoated Ti6Al4V substrate, the maximum indentation depth exceeded 175 nm at an applied load of 2000 μN. After unloading, the calculated contact depth was 134 nm. The substrate exhibited an elastic modulus of 81.4 GPa and a hardness of approximately 4 GPa. After deposition of the Ti–Au coating (Sample 1), a noticeable improvement in mechanical properties was observed. Under the same loading conditions, the maximum indentation depth decreased to 102.8 nm, while the contact depth after unloading was 67 nm. The elastic modulus and hardness increased to 190.8 GPa and 12.6 GPa, respectively, confirming the formation of a relatively hard and mechanically stable coating. For the Ti–Au–Ag coating (Sample 2), the maximum indentation depth reached 132 nm, with a contact depth of 75 nm after unloading. The measured elastic modulus was 168.1 GPa, while the hardness increased to 13.2 GPa. In the case of the Ti–Au–Ag–N coating (Sample 3), the indentation depth was reduced to 91 nm and the contact depth after unloading was 61 nm. At the same time, the elastic modulus increased significantly to 251.2 GPa,

accompanied by a hardness of 16.8 GPa. The Ti–Au–Cu coating (Sample 4) showed a maximum penetration depth of 100 nm and a contact depth of 62.5 nm after unloading. Its elastic modulus reached 282.5 GPa, while the hardness was 16.2 GPa. For the nitrogen-modified Ti–Au–Cu–N coating (Sample 5), the maximum indentation depth was 104 nm, with a contact depth of 64.4 nm. The corresponding elastic modulus and hardness were 219.8 GPa and 17.3 GPa, respectively. Among the investigated coatings, the Ti–Au–Cu–N sample demonstrated the highest hardness, indicating that nitrogen modification had a positive effect on the mechanical performance of the coating.

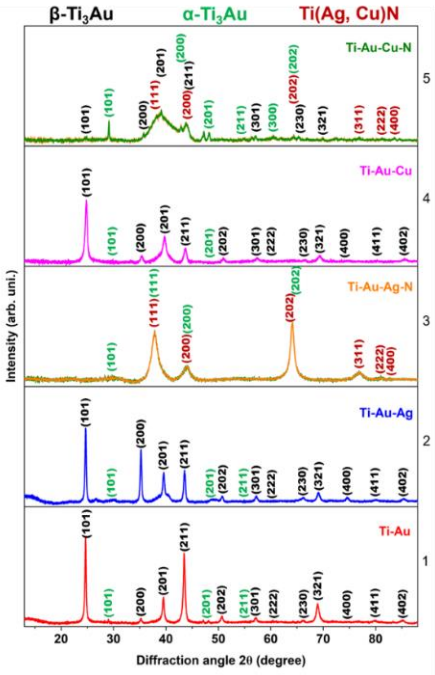


Figure 9. X-ray diffraction (XRD) patterns of Ti–Au-based coatings deposited by the NanoPVD method

Note – compiled by the authors

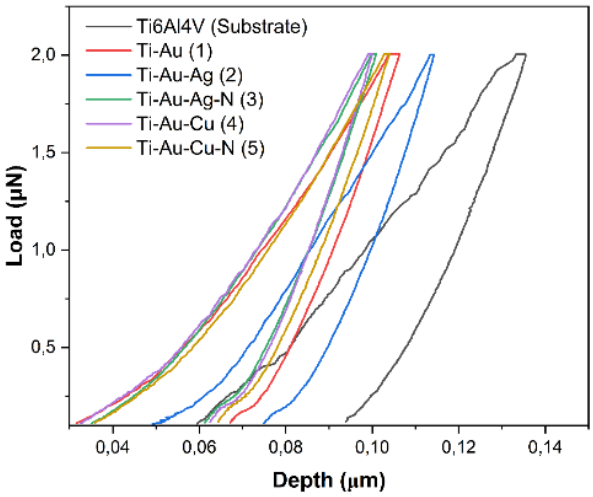


Figure 10. Load–displacement curves obtained from nanoindentation tests of the Ti–Au-based coating and the Ti_6Al_4V substrate

Note – compiled by the authors

The wear resistance results are presented in Figure 11, illustrating the comparative tribological behavior of the Ti–Au-based thin-film coatings and the uncoated Ti6Al4V substrate. The average coefficient of friction (COF) of the uncoated Ti_6Al_4V substrate was 0.587 ± 0.058, indicating the relatively high frictional response of the alloy under sliding conditions. The Ti–Au coating (Sample 1) exhibited a substantially lower coefficient of friction of 0.202 ± 0.028, corresponding to an approximately threefold reduction compared with the uncoated substrate. The Ag-alloyed Ti–Au–Ag coating (Sample 2) demonstrated the lowest average coefficient of friction (0.177 ± 0.019), indicating that Ag incorporation optimized the coating microstructure and improved the sliding contact conditions. In contrast, the nitrogen-modified Ti–Au–Ag–N coating (Sample 3) exhibited a somewhat higher coefficient of friction (0.430 ± 0.124), which can be attributed to the formation of additional phases and microstructural changes induced by the nitriding process that influenced its tribological behavior. The Ti–Au–Cu coating (Sample 4) showed an average coefficient of friction of 0.312 ± 0.067, whereas the nitrogen-modified Ti–Au–Cu–N coating (Sample 5) exhibited a lower value of 0.229 ± 0.037. These results indicate that Cu alloying followed by nitrogen modification contributed to an improvement in the tribological stability of the coating.

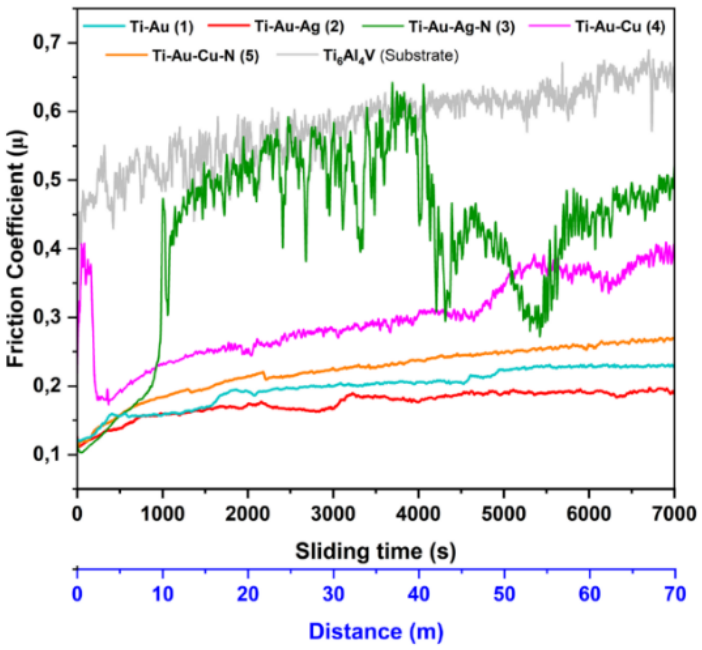


Figure 11. Tribological test results showing the coefficient of friction (COF) of the Ti–Au-based coatings and the Ti_6Al_4V substrate

Note – compiled by the authors

Overall, all fabricated thin-film coatings exhibited a substantial reduction in the coefficient of friction compared with the uncoated Ti_6Al_4V substrate. This improvement is directly associated with the increased hardness of the coatings and the enhanced mechanical stability of their surface layers. These findings are in excellent agreement with the nanoindentation results, where the simultaneous increase in hardness and decrease in the coefficient of friction confirm the superior wear resistance of the coatings and demonstrate their effectiveness as protective anti-wear layers.

CONCLUSIONS

In summary, the results of this study demonstrate that Ti–Au-based thin-film coatings deposited by the NanoPVD technique possess an average thickness of approximately 1 μm, and

their properties are strongly dependent on the deposition parameters. The incorporation of silver (Ag) and copper (Cu) significantly influences the coating morphology, increasing the average surface roughness to 17.4 ± 1.8 nm and 13.5 ± 2.7 nm, respectively, whereas nitrogen treatment reduces the surface roughness to 2.3 ± 0.8 nm.

X-ray diffraction (XRD) analysis confirmed the formation of the β-Ti_3Au phase as the predominant phase, while the appearance of TiN and α-Ti_3Au phases was observed following nitrogen modification. Nanoindentation measurements revealed significantly improved mechanical properties compared with the Ti6Al4V substrate, with the Ti–Au–Cu–N coating exhibiting the highest hardness (17.3 GPa) and an elastic modulus of 219.8 GPa.

Tribological testing demonstrated a marked reduction in the coefficient of friction and enhanced wear resistance of all coatings. Therefore, the fabricated Ti–Au-based coatings exhibit an optimized surface morphology, high mechanical strength, and excellent wear resistance, making them promising candidates for application as protective coatings on mechanical and biomedical applications.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

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