Research Article

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Tribological investigation of multilayer CrN/CrCN/TaN films deposited by close field unbalanced magnetron sputtering

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Abstract: CrN/CrCN/TaN multilayer films were deposited onto the CoCrMo alloy substrates at different number layers as two, four and 8 layers by close-field unbalanced magnetron sputtering method. Microstructure and the tribological properties of the films were characterized by XRD, SEM, pin-on-disk wear test, scratch test, micro hardness. CrN/CrCN/TaN multilayer coatings exhibited good adhesion properties on the CoCrMo alloy substrate. A very high hardness value of 60 GPa was obtained for 8 multilayered coating. As a result of the pin-on-disc wear tests, it was found that the tribological properties of the CoCrMo alloy were enhanced by coating its surface with this architecture by using close-field unbalanced magnetron system with used parameters.

Keywords: Biomaterial, CoCrMo alloy, PVD coating, Tribology, Tantalum Nitride

1 Introduction

Biomaterial science has been developing parallel to advances in material science and technology. In addition to classic biomaterials, investigations on topics like shape memory alloys, composites with high tissue compatibility are steadily increasing [1]. But still, it is thought that the use of metal alloys will continue, until an alternative material has been developed which can be substitute that are especially used as artificial joints due to their mechanical properties [2, 3].

Metallic biomaterials which are used in artificial joint applications are worn by exposing to tribocorrosion in vivo and hence metal and polyethylene debris are released into

the body fluid. This debris causes to allergic and toxic effects as a result of accumulating in and next to tissues, and finally causes to loosening the implant [4]. CoCrMo alloys are widely used at artificial joint applications due to their good mechanical properties like high modulus of elasticity, high tensile strength, high wear and corrosion resistance [5]. However, these alloys have low wear strength at frictional environment under load. When used in vivo, it wears readily by exposing to tribocorrosion and releases Cr+2 and Co+2 into the body fluid which can cause allergic affects [6]. In order to avoid the metal ionization and enhance the corrosion resistance of biomaterials, some surface treatments are applied. Coating of the implant surfaces is one of these preventive measures [7]. TiN, ZrN, CrN, alumina, diamond like carbon (DLC) coatings can be given as examples of mostly used ceramic coatings [8]. Besides the biocompatibility, the common features of these ceramic coatings are enhancing the hardness, elasticity modulus, wear and corrosion strength of the surface of the biomaterials they coat [9].

Some investigations had been performed to decrease the metal ion release and enhance the wear and corrosion strength of the CoCrMo alloy by coating its surface with a ceramic thin film layer. There are some studies had been performed on the coating of the surface of CoCrMo alloy with one or multilayered diamond-like carbon (DLC) films. When we look at the results of these studies, it can be seen that the tribocorrosion strength of the alloy was significantly enhanced [10, 11]. Some researchers have studied the coating of the surface of the CoCrMo alloy with Ti and TiN or TiO compounds due to its high corrosion resistance [12, 13]. In these studies, increased corrosion and wear resistance values were obtained.

The uses of TaN ceramic coatings are also becoming widespread due to many important properties such as high biocompatibility, corrosion resistance close to noble metals, high hardness, and elasticity modulus [14, 15].

Mendizabal *et al.* [16] have deposited single and multilayer TaN coatings on the pure Titanium substrates by HPPMS (high power pulsed magnetron sputtering) PVD

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method. The results of conducted wear tests showed that; while the friction coefficient of commercial pure titanium was 0.58, obtained value was 0.25 for multilayer coated samples and significantly decreased wear rate was obtained. Liu *et al.* [17] have coated amorphous and crystalline structure multilayer TaN on the AISI 420 and silicon stack substrates separately by magnetic reactive sputtering method. They reported significantly enhanced wear resistance and adhesion properties for multilayer coated samples compared to single layer coatings. Hee *et al.* [18] have studied the corrosion and adhesion properties of the pure Ta and Ti/Ta coatings which are deposited on the Ti6Al4V substrates by physical vapour deposition. They measured the corrosion current density values as 2×10^{-8} A/cm² and $3,4 \times 10^{-9}$ A/cm² respectively for Ti6Al4V and multilayer Ti/Ta coated sample. Jara *et al.* [14] have deposited Ta, TaN and Ta/TaN thin films on the pure titanium and SS 316 LVM substrates respectively by radio frequency sputtering technique. They reported that the substrate material affects not only the formed phase but also the microstructure and the surface roughness of the deposited films. Balagna *et al.* [19] coated the surface of CoCrMo alloy with Ta based coatings in order to decrease the metal release and also to decrease the wear rate of the ultra-high molecular weight polyethylene (UHMWPE) which is usually used as counter part of this alloy in artificial joint applications. They have achieved, two-fold increase in the hardness value and significantly enhanced wear strength for multilayer coated sample compared to bare CoCrMo.

As seen by the presented previous works, only small amount of study has been carried out about the multilayer surface coating of ASTM F75 CoCrMo alloy with TaN based coatings. Therefore, in this study our aim was to coat the surface of this alloy with Ta based functionally graded multilayer coatings by closed field unbalanced magnetron sputtering system, which can benefit artificial joint application processes. Coatings have been deposited with CrN/CrCN/TaN coating architecture with different layer numbers. Adhesion and tribological properties of the coatings were investigated by conducting characterization experiments.

2 Experimental details

2.1 Material

The tibial tray of total knee implant was used as raw material and supplied from a commercial implant manufacturer company (Ottoman Implant Company). The samples

were cut off to dimensions 25×25×2.5 mm by a laser cutting system. Due to the high hardness of the alloy, the polishing process was started with 120 mesh grit and continued with respectively 240, 400, 600, 1000 and finally polished with 1200 mesh grit SiC emery paper. After polishing, the samples were ultrasonically cleaned in acetone and rinsed with the deionized water. Prior the deposition, all the substrates argon-ion-etched for 25 minutes using a substrate bias of –800 V with a pressure of 0.33 Pa.

2.2 Method

TaN multilayer coatings were deposited on the CoCrMo alloy substrates by closed field unbalanced magnetron sputtering method. A thin Cr adhesion layer was deposited on the substrate firstly. Then, a CrCN layer with a hardness of 2400 HV deposited, following a CrN layer with a hardness of 1100 HV was deposited. For the top coating layer, TaN was selected due to its superior mechanical properties such as high hardness, high wear, and corrosion strength. Therefore, a functionally graded coating architecture was developed in terms of hardness. Three different coating models designed in order to investigate the effect of the CrN/CrCN bilayer and the number of the layers on the wear performance of the coatings. Figure 1 depicts the schematic representation of the coating architectures.

Figure 1: Coating architectures of the samples illustrated in 2D

The coating deposition process was performed by using a closed field unbalanced magnetron sputtering system (Teer Coatings) which has four targets and 2 DC power supplies. One tantalum target with a purity of %99,95 and one Cr target with a purity of %99,95 was located to the device. All the deposition parameters were selected on previous studies and then optimized with the Taguchi method [15–17, 20–23]. During the sputtering process, 4

Table 1: Coating Parameters

	Cr	CrCN	CrN	TaN
Bias (V)	–150	–150	–100	–100
Target Current (A)	4	4	4	4
N ₂ Flow rate (sccm)	-	14	14	14
C ₂ H ₂ flow rate (sccm)	-	5	-	-
Deposition Time (min)	3	10	10	800

Ampere current was applied to the targets while working pressure was kept at 0.33 Pa. Cr layer was deposited at –150 V bias voltage for 3 minutes. –100 V bias voltage was applied to the substrate with a pressure of 0.33 Pa for 10 minutes during the deposition of CrN layers. CrCN layer deposition was performed at a substrate bias of –150 V for 5 minutes. In order to deposit ternary compound coating layer N₂ and C₂H₂ gases were introduced into the chamber with a flow rate of 14 and 5 sccm respectively. The top coating layer TaN was deposited with a pressure of 0.33 Pa for 800 minutes at a –100 V bias voltage to the substrate. Details of the coating parameters are given in Table 1. In order to evaluate the coating thickness, the deposition process was performed on glass substrates using the same parameters.

XRD analysis were performed at a wavelength of $\lambda=1.5405 \text{ \AA}$, in the scanning range of $2\theta=3-80^\circ$ with a speed of 2° min^{-1} , in order to determine the phase analysis of the coated surfaces. Microstructure and the thickness of the deposited films were investigated by using a Levo Evo Scanning electron microscope operated at 20 kV. Micro hardness measurements were performed by using a (Buehler Micromet 2001) micro hardness device. 25 gf static force was applied on the coating surfaces. The surface roughness (Ra) of the samples was measured using a surface profilometer (TIME TR 200) with sensitivity of 0.01–0.04 μm .

Progressive scratch tests were performed using a Revetest micro scratch device which has detectors to collecting data for friction force and acoustic emission to evaluate the adhesion of the coatings. The device has an optical microscope to display the scratch deformation modes and to associate them with the applied load. Scratch testing was performed with a starting load of 0.2 N. The loading rate was 100 N/min and the sliding velocity was 10 mm/min.

Tribological properties of the coatings were investigated by performing dry sliding wear tests, using a pin-on-disc tribometer device (CSM Pin-on-disk Tribometer). Experiments were conducted at dry conditions with a temperature of 25°C and humidity rate of 45%, by using an alumina (Al_2O_3) ball with a diameter of 6.25 mm as the coun-

terpart. The sliding velocity of the pin was $10 \text{ cm}\cdot\text{s}^{-1}$ and the applied load onto the sample surface was 1N with a frequency of 60 Hertz. SEM and EDS analyses were performed on the wear tracks of the samples in order to characterize and understand the wear mechanism more thoroughly. The worn cross-sections of the coatings after dry sliding wear tests were evaluated by wear track profile measurements using a Park XE Atomic Force Microscope. Then wear rates of the samples were calculated by the following equation [24]:

$$W_r = V/F \cdot S \quad (1)$$

where the W_r is the calculated wear rate ($\text{mm}^3/\text{N m}$), V is the wear volume (mm^3), F is the normal load (N) and the S is the sliding distance (m).

3 Results and discussions

3.1 Coating characterization

In all the coating models, in order to enhance adhesion between the substrate and the coating layers, Cr adhesion layer was deposited firstly. Figure 2 shows the cross-section SEM image of the C3 coating on the glass substrate. As can be seen in the Figure 2, the coating layers exhibited a dense columnar structure. The coating layers of C1 and C2 showed similar structure too. The reason for this can be explained by the fact that substrate material has been bombarded with high energy ions that sputtered from the Cr and Ta targets. Also, it can be said that the applied appropriate bias voltage to the substrate material, lead to the deposition of the ions from the plasma onto the substrate surface to form a dense film layer [25].

Figure 2: Cross section SEM image of C3 coating

Figure 3: SEM image of the surface of the C3 coating

Although all the coating parameters were same, the measured thickness of the individual coatings was not the same as for the same layers. Total thickness of the coatings C1, C2 and C3 were respectively $1.031\ \mu\text{m}$, $2.000\ \mu\text{m}$ and $3.610\ \mu\text{m}$. This non-equilibrium of the thickness values can be explained by be changing of the substrate material for all coating layer. In order to obtain equal coating thickness, it is necessary to experimentally optimize all coating models separately.

It is known that the particle size significantly affects the mechanical properties of the materials and this is the same applies to the coatings too [26, 27]. In order to investigate the particle size of the coating's SEM analyze was applied on the surface of the C3. As can be seen in Figure 3 coating surface has a dense and homogeneous structure without any porosity. The particle size of the coating was calculated by The particle size of the coating is averagely 200 nm.

The XRD patterns of the coatings are shown in Figure 4. As can be seen from the figure, all coatings exhibited a crystalline structure. Face centered cubic structured TaN phase with (111), (200) peaks are shown at respectively at 2θ degrees of 35° and 40° . Forming of fcc-TaN structure was seen on previous TaN coating studies which were performed by the PVD process [15, 23, 28–32]. When the XRD pattern of Cr/CrN/CrCN/TaN coating is studied, a mixed structure of fcc-TaN and an hcp-Ta₂N phase with (102) peak was seen, which was not present in the other coatings. Cheviot *et al.* have reported that the process parameters such as target power density, N₂ partial pressure, total gas pressure and distance of substrate-target, affects the forming of fcc-TaN and h-TaN and the weight ratio of these structures [32]. But in this study, all the coatings were deposited with the same parameters. Therefore, forming of a mixed

Figure 4: Xrd patterns of the coatings

structure of h-Ta₂N and fcc-TaN in the C3 coating cannot be explained by this way. In this case, we think that forming of this mixed structure can be explain by the thermo mechanical stress of the deposited film [32, 33].

3.2 Adhesion Properties

Adhesion of the hard coatings to the substrate material is one of the most important features that determine the success of the coating. While the critical load Lc1 is defined as the load of initial cohesive failure, the critical load Lc2 is defined as the initial of the adhesive failures. And the fully delamination of the coating is described as Lc3 [34]. Mainly two different mechanisms of detachment of the coatings were noticed as cohesive and adhesive failures which is predominantly dependent on the coating structure.

(a)

(b)

(c)

Figure 5: Progressively loading-acoustic emission of a- C1 b-C2 c-C3 coating

Figure 5(a) depicts the acoustic emission-force graph of the two-layer coated C1 sample. Optical microscope (OM) images of the scratch tracks that were taken at different loads are given below the graph. When the Figure 5 is studied, it can be clearly seen that the deformations on the coatings consisted of little cracks and detachments at the rims of the scratch track. Cohesive deformation formed approximately at a load of 8 N, and the character of the deformation mechanism was cohesive till 62 N load. The critical load L_{c2} was obtained for C1 sample about 62 N and, above 68 N load, it was observed that adhesive delamination started and exposed substrate material areas displayed.

For 4 layered coated C2 sample, cohesive failures formed approximately between of 17-54 N in the film layer and this can be seen from the Figure 5(b) which shows the acoustic emission-force graph of the sample. The fluctuations on the emission graph mean deformation mechanism is cohesive and consisted of little cracks and detachments at the rims of the scratch track in this load range. Above 54 N loads till 67 N deformation mechanism is still cohesive but the scratches are bigger and buckle spallation shaped. It is observed that adhesive failures were started above the load of 67 N and finally at the load of 84 N load substrate material was fully appeared. Figure 5(b) shows the acoustic emission-force graph of the 4-layer coated C2.

Cohesive failures of the 8 layers coated C3 sample started approximately 23 N and the cohesive and buckle spallation failures formed in the film layer under the load of approximately till 62 N. Critical load L_{c2} value was found 67 N for this sample, and fully delamination of the coating was observed at a load of about 94 N. Acoustic Emission and optical microscope images of the C3 coating can be seen in the Figure 5(c).

According to the scratch adhesion test results of all samples, it is understood that lower than approximately loading values of 50 N, cohesive failures were formed at the rims of scratch track and in the film layer without appearing the substrate material. Calculated L_c values are given in Table 2. Using of CrN/CrCN as interlayer increased the adhesion of the coatings. Starting load of initial cohesive failures were 2-fold increased as for C2 compared to C1. For

Table 2: Critical loads

Coatings	Critical Loads (N)		
	L_{c1}	L_{c2}	L_{c3}
C1	8	62	68
C2	17	64	84
C3	23	67	94

Table 3: COF and wear rates of the coatings

Coating	Coefficient of Friction	Wear Rate [mm ³ ·N ⁻¹ ·m ⁻¹]
C1	0.177	4.227×10 ⁻⁵
C2	0.145	0.463×10 ⁻⁵
C3	0.143	0.372×10 ⁻⁵

8 multilayer C3 this value was approximately 3-fold compared to C1. Although obtained Lc2 values were close to each other, the interval between critical loads Lc2 and Lc3 was differentiated due to the number of the layers. The appearance of the substrate material was observed at higher loads due to the Increasing the number of the layers. As a result of the C3's scratch test, although substrate material can be seen, still coating areas were present even at the load of 120 N.

Nordin *et al.* have deposited TiN/CrN, TiN/MoN, TiN/NbN and TiN/TaN multilayer coatings on cemented carbide substrate [34]. They had obtained 38 N critical load for TiN/TaN coating layer. Balagna *et al.* coated CoCrMo alloy surface via thermal treatment in molten salts with Ta based coating layers [19]. They revealed critical loads of 11 N, 22N and 25 N for TaC coated three different samples. Yang and Wu coated AISI 420 steel surface with multilayer TaN [36]. They deposited coatings with two different layer number as 20 layers and 50 layers. They revealed initial plastic deformation load values of 31.6 N and 31.2 N for 20 layers coated and 50 layers coated samples respectively. They also reported that the probable cause to obtain close critical load values for both coatings could be related to the amorphous-crystalline structure of the 20 layered coating. Baran *et al.* have investigated the adhesion and fatigue properties of TiN/TaN multilayer coatings on W and Mo substrates [16]. As a result of progressive loading scratch tests, they obtained critical load values of 32 N and 42 N for on Mo and on W substrate respectively. When our experimental results compared to that of literature data, it can be seen clearly that CrN/CrCN/TaN coating deposited on CoCrMo alloy by closed field unbalanced magnetron sputtering method showed better adhesion properties. But it must be noticed that the adhesion property of a coating on a substrate depends on many factors such as used substrate material, deposition technique, and parameters, structure, and the thickness of the films, etc. In order to make a better comparison, some common experimental parameters must be evaluated.

3.3 Tribological Properties

While studying the tribological properties of the coatings, characterization of the wear mechanism is important as well as determining the coefficient of friction (COF) and wear volume. Therefore, SEM micrographs of the worn surfaces were taken. Coefficient of friction and wear rates of the samples are given in the Table 3. As a result of the dry sliding wear test of the Cr/TaN coating, the friction coefficient was calculated to be around 0,177. Coefficient of friction obtained from dry pin on disk test of bare CoCrMo alloy with alumina ball at low loads was 0,45. Wear rate of the C1 sample under 1N loading was calculated as 4.227×10⁻⁵ mm³/Nm. When COF of C1 compared to this value it was understood that the wear resistance of alloy surface was improved significantly. Figure 6a show the SEM image of worn surface of the C1. As can be seen from the figure, wear mechanism is predominantly abrasive wear. Adhesive abrasions are seen in microstructure in a small amount and without continuity. The worn particles which form as a result of abrasive wear act as a third body between alumina and sample surface. Some pitting corrosion areas were observed on the worn surfaces too, this can be related to oxidation that occurred while performing wear tests at atmospheric environment.

When the wear results of Cr/CrN/CrCN/TaN surface are studied, it was understood that the deposition of CrN/CrCN bilayer between Cr and TaN layer, decreased the coefficient of friction significantly. The coefficient of friction between alumina ball and C2 sample was calculated to be around 0.145 and this was less than the value of COF of C1 sample. The wear rate of the C2 sample was calculated as 0.463×10⁻⁵ mm³/Nm and this was 9 times less than of the C1 wear rate. Using CrN/CrCN interlayer between the Cr adhesion layer and TaN layer decreased the coefficient of friction and wear rate significantly, hence it can be said that the wear resistance is increased. Figure 6b depicts the SEM micrograph that taken at 2500× magnification on the wear track of worn surface of C2 sample. Looking at this figure, we can see that the main wear mechanism is abrasion for this sample too. Besides, pitting corrosions are seen in a small amount.

Coefficient of friction of C3 sample with a value of 0,143 was less than the coefficient of friction values of both C1 and C2. Wear rate of the C3 is calculated as 0.372×10⁻⁵ mm³/N.m. Although COF values of C2 and C3 is close, wear rates of the samples are not closer [37–39]. SEM micrograph of the worn surface of the C3 sample is given in Figure 6c. As can be seen in the figure, wear track shows less evident scratches and grooves, than C1 and C2. The

Figure 6: SEM image of worn surface of a- C1 b- C2 c- C3 Coating

scratches on the rims of the wear tracks are not related to wear test and probably formed from the polishing process.

Yıldız coated the surface of AISI M24 HSS with TaN, ZrN, and TaN/ZrN. As a result of dry reciprocating wear tests which was applied by alumina ball, he revealed that the coefficient of friction value of 0,18 for one-layer TaN coating. For 4 and 8 layered TaN/ZrN multilayered coatings, he reported COF values 0,63 and 0,68 respectively [39]. Chen *et al.* studied the structural and mechanical properties of the TaN/aCN films deposited on Ti substrates [12]. They have applied dry pin on disk wear tests for coatings by using a Si₃N₄ ceramic ball. They reported 0.35 coefficient of friction value and $1.6 \times 10^{-14} \text{ m}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ wear rate for TaN coating. Zaman has studied the tribological characterization of TaN coatings that deposited on Si wafer substrates by plasma enhanced chemical vapor deposition method [31]. She reported 0.9 coefficient of fric-

tion value and $3.1 \times 10^{-6} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ wear rate as a result of dry pin on disk experiments which was performed by using an alumina ball as counterpart.

When the three-coating compared to each other, it was observed that C3 has the best wear resistance. Using of CrN/CrCN as an interlayer has decreased the wear resistance significantly compared to two layered C1 sample. The COF of C2 and C3 was very close to each other, therefore further experiments are required in order to evaluate the best coating architecture in terms of wear properties. On the other hand, when the wear results were compared to the literature data, although applied experimental procedures differentiate, it can be seen that lower wear rates have obtained therefore the coating is effective in enhancing the wear resistance in all cases.

Table 4: Micro hardness and Surface Roughness Results of the Samples

Sample	Bare CoCrMo	C1	C2	C3
Micro Hardness (Gpa)	8.31	24	34	60
Roughness Ra (μm)	0,065	0,048	0,025	0,020

3.4 Hardness and Surface Roughness

Table 4 summarizes the micro hardness and surface roughness of the samples. Micro hardness of the bare CoCrMo alloy was calculated as 8.31 GPa. It is understood that the hardness value increased approximately 3 folds by coating with Cr/ TaN compared to the hardness of the bare alloy. According to the hardness results, it can be observed that hardness increased proportionally to the increment of the layers. But it must be noticed that the hardness is not only affected by the number of the layers but also the thickness of the deposited films too. When the thickness values of the coating films are considered, it is seen that the order of magnitude between the hardness values is the same as the thickness values. For 8 layered coating, the highest hardness value was obtained thanks to functionally graded multilayered coating architecture in terms of hardness. It was also understood that deposition of CrN/CrCN bilayer as an interlayer for C3 coating enhanced the hardness value approximately 3-fold compared to coating C1. This result is in agreement with the literature data [21–23]. The surface roughness is an important factor for wear properties of the hard-thin films [26]. While the surface roughness of the bare CoCrMo was measured about 65 nm in terms of Ra value, the surface roughness values of the coated samples were lower than the bare alloy and calculated as 48 nm, 25 nm, and 20 nm respectively for C1, C2, and C3.

Nordin *et al.* [35] reported approximately 35 GPa hardness for TiN/TaN multilayer coating with a thickness of 3.5 μm. Ma *et al.* [40] revealed maximum hardness value of 12.93 GPa for Ta/TaN multilayered coating with a thickness of 1.167 μ. Yang *et al.* [27] have obtained the highest hardness value of 26 GPa for monolayer TaN coating deposited on the AISI 420 with a thickness of 1040 nm. Zaman [30] has calculated 38.23 GPa hardness value for TaN coating with a thickness of approximately 10 nm which was deposited at –300 V bias voltage. Liu *et al.* [17] have reported 21.1 GPa hardness value for c-TaN layer with a thickness of 1 μ. Baran *et al.* [16] have obtained 44 GPa hardness value for TiN/TaN multilayer coating on W substrate. Yang and Wu [36] have coated TaN multilayer coatings on AISI 420

steel substrates via RF sputtering. They obtained 15.1 GPa micro hardness value for 50 layered coating with a thickness of 2 μm.

When our experimental results compared to literature data, it is concluded that high micro hardness values were obtained.

4 Conclusions

TaN based multilayer coating films were deposited on the CoCrMo alloy surface with three different coating architecture successfully via closed field unbalanced magnetron sputtering system. As a result of the conducted characterization experiments, we can conclude that; this multilayer coating architecture showed good adhesion properties with the surface of the CoCrMo alloy. Using of CrN/CrCN as an interlayer provided better surface properties in terms of hardness, scratch and wear resistance compared to 2 layered coated samples. 8 multilayered coating showed the best wear rate as $0.372 \times 10^{-5} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$. Tribological properties of the CoCrMo alloy can be enhanced by coating its surface with this architecture by using close-field unbalanced magnetron system with used parameters. Additionally; in order to use this coated alloy as a biomaterial, some further experiments are required such as biocompatibility and corrosion tests in the simulated body fluid.

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References

- [1] W. Wei, R. Cheng, J. Neves, J. Tang, J. Xiao, Q. Ni, X. Liu, G. Pana, D. Lia, W. Cuia and B. Sarmento, J. Controlled Release, 261 (2017) 318–336.
- [2] N.S. Manam, W.S.W. Harun, D.N.A. Shri, S.A.C. Ghani, T. Kurniawan, M.H. Ismail and M.H.I. Ibrahim, J. Alloys Compd., 701 (2017) 698–715.
- [3] J. Wilson, Metallic biomaterials: State of the art and new challenges in: Fundamental Biomaterials: Metals, Woodhead Publishing, (2018) UK, pp. 1–33.
- [4] S. Affatato, Wear of orthopedic implants and artificial joints, Woodhead Publishing Limited, UK, (2012).
- [5] J. Park, R.S. Lakes Biomaterials-An Introduction (3. Edition), Springer, USA, (2007).
- [6] B. Love, Biomaterials: A Systems Approach to Engineering Concepts, Academic Press, (2017), pp. 159–184.

- [7] B.J. McEntire, B.S. Bal, M.N. Rahaman, J. Chevalier and G.J. Pezzotti, *Eur. Ceram. Soc.*, 35 (2015) 4327-4369.
- [8] C. Wien, *Surface Coating and Modification of Metallic Biomaterials*, Woodhead Publishing, UK, (2015).
- [9] J. Park, *Bio ceramics: Properties, Characterizations and applications*, Springer, USA, (2008).
- [10] L.J. Jia, W.X. Xue, B.J. Wu, T.F. Zhang, Y.X. Leng and N. Huang, *Vacuum*, 92 (2013) 39-43.
- [11] T. Di, D. Mingjiang, F. Wenbin, L. Songsheng, W. Chunbei and Z. Mingchun, *Rare Met. Mater.*, 44 (2015) 2982-2986.
- [12] R. Chen, J.P. Tu, D. G. Liu, Y.L. Yu, S.X. Qu and C.D. Gu, *Surf. Coat. Technol.*, 206 (2012) 2242-2248.
- [13] U. Türkan, O. Öztürk and A.E. Eroğlu, *Surf. Coat. Technol.*, 200 (2006) 5020 – 5027
- [14] A. Jara, B. Fraisse, V. Flaud, N. Frety and G. Gonzalez, *Surf. Coat. Technol.*, 309 (2016) 887-896.
- [15] Ö. Baran, E.E. Sukuroglu, İ. Efeoglu and Y. Totik, *J. Adhes. Sci. Technol.*, 30 (2016) 2188-2200.
- [16] L. Mendizabal, A. Lopez, R. Bayón, P. Herrero-Fernandez, B.J. Javier, J. Javier and J.J. Gonzalez, *Surf. Coat. Technol.*, 295 (2016) 60-69.
- [17] K.Y. Liu, J.W. Li and F.B. Wu, *Surf. Coat. Technol.*, 259 (2014) 123–128.
- [18] A.C. Hee, S.S. Jamali, A. Bendavid, P.J. Martin, C. Kong and Y. Zhao, *Surf. Coat. Technol.*, 307 (2016) 666-675.
- [19] C. Balagna, M.G. Faga and S. Spriano, *Mater. Sci. Eng.*, 32 (2012) 887–895.
- [20] J.W. Lee, S.K. Tien and Y.C. Kuo, *Thin Solid Films*, 494 (2006) 161–167.
- [21] A.L.P. Reyna, B. Fritz, J. Schwiesau, C. Schilling, B. Summer, P. Thomasa and T.M. Grupp, *J. Biomech*, 79 (2018) 88–96.
- [22] B. Warcholinski and A. Glewicz, *Plasma Processes and Polym.*, 8 (2011) 333–339.
- [23] A. Aryasomayajula, K. Valletti, S. Aryasomayajula and D.G. Bhat, *Surf. Coat. Technol.*, 201 (2006) 4401–4405.
- [24] K. Holmberg and A. Matthews, *Coatings Tribology: Properties, Mechanisms, Techniques and Applications in Surface Engineering*, Elsevier Science & Technology, UK (2009).
- [25] M. Ohring, *Materials Science of Thin Films Deposition and Structure*. Academic Press, USA (2002).
- [26] B.D. Sartwell, G.E. McGuire and S. Hofman, *Proceedings of the 19th International Conference on Metallurgical Coatings and Thin Films* (1992).
- [27] Y.H. Yang, D.J. Chen and F.B. Wu, *Surf. Coat. Technol*, 303 (2016) 32–40.
- [28] R. Chen, J.P. Tu, D.G. Liu, Y.L. Yu, S.X. Qu and C.D. Gu, *Surf. Coat. Technol.*, 206 (2012) 2242–2248.
- [29] M. Alishahi, F. Mahboubi, K.S.M. Mousavi, M. Aparicio, R. Hübner, F. Soldera and R. Gago, *J. Power Sources*, 322 (2016) 1-9.
- [30] A. Zaman and E.I. Meletis, *Coatings*, 7 (2017) No:12-209.
- [31] C. Angelkort, A. Berendes, H. Lewalter, W. Bock and B.O. Kolbesen, *Thin Solid Films*, 437 (2003) 108–115.
- [32] M. Cheviot, M. Gouné and A. Poulon-Quintin, *Surf. Coat. Technol.*, 284 (2015) 192–197.
- [33] A. Poulon-Quintin, C. Faure, L. Teulé-Gay and J.P. Manaud, *Mater. Sci. Forum*, 706 (2012) 2898-2903.
- [34] M. Berni, N. Lopomo, G. Marchiori, A. Gambardella, M. Boi, M. Bianchi, A. Visani, P. Pavand, A. Russo and M. Marcacci, *Mater. Sci. Eng. C*, 62 (2016) 643–655.
- [35] M. Nordin, M. Larsson and S. Hogmark, *Surf. Coat. Technol.*, 106, (1998) 234-241.
- [36] Y.H. Yang and F.B. Wu, *Surf. Coat. Technol.*, 308 (2016) 108–114.
- [37] A.F. Yetim, M. Aslan, F. Yıldız, İ. Hacısalıhoğlu and Ö. Bayrak, *Engineer and Machine*, 53 (2012) 37-43.
- [38] D.W. Gebretsadik, J. Hardell, İ. Efeoglu and B. Prakash, *Tribology*, 5 (2011) 100-106.
- [39] O. Yıldız, *Investigation of wear properties of TaN, ZrN and TaN/ZrN multilayer thin film coatings*, PhD Thesis, Technical University of İstanbul, Turkey (2010).
- [40] G. Ma, G. Lin, S. Gong, X. Liu, G. Sun and H. Wu, *Vacuum*, 89 (2013) pp. 244-248.