The Effect of Coatings on the Wear Behavior of Ti6Al4V Alloy Used in Biomedical Applications

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Abstract: The properties expected from implant materials are biocompatibility, long service life and wear resistance. The wear resistance of the implant materials varies according to the type of implant, usage area and the movement. The ability of implant material to be more compatible with biological tissues and to increase the useful life depends on the surface properties. Today many different kind of surface modification techniques are applying on medical and dental implant surfaces to improve surface specifications and wear resistance.

In this study TiN, TiAlN, TiCN coatings were applied on Ti6Al4V alloy used as implant material by reactive magnetron sputtering method. The wear resistances of uncoated Ti6Al4V alloy and TiN, TiAlN, TiCN coatings were investigated at room temperature under dry conditions. The wear resistance at different load and different sliding rates were compared using an wear tester. The wear losses, wear track widths and friction coefficients of coated and uncoated Ti6Al4V alloys are taken into account for comparison. The results show that a significant improvement in wear resistance of the alloy with the coating is achieved and TiN-coated Ti6Al4V alloy has the highest wear resistance.

Keywords: Biomedical, Ti6Al4V alloy, TiN, TiAlN, TiCN coatings, wear.

1. Introduction

Although it is a new field in the scientific sense, the use of biomaterials extends to ancient times in history. The use of gold in dentistry extends up to 2000 years ago. Since the middle of the 19th century serious progress has been made in the use of different materials in the body. During the last 30 years important information has been obtained about understanding the interactions of biomaterials in the body[1-3]. Metallic biomaterials are one of the best materials that best match the mechanical conditions. This is because metallic biomaterials can withstand long-term, variable and sudden loadings without losing their properties[4,5]. The body has a dynamic environment that will create high wear conditions for metals[4-6]. The use of materials with as high a wear resistance as possible provides great convenience in medical applications. The main current problem with implants is the nature of the implant-tissue interface[7-10]. In recent years there has been a serious increase in the use of titanium and titanium alloys. Because titanium alloys have these advantages such as strength, rigidity, low density, corrosion resistance. However, the tribological properties of the most commonly used Ti6Al4V alloy in the biomedical field are not sufficient[11-13]. Improving the surface
characteristics of the implant materials is very important. In order to reduce wear, researchers follow two paths: (i) use new, wear resistant materials or (ii) improve the wear resistance of materials by adding alloying elements or performing surface treatments. Thin film hard nitride coatings are seen as a viable way to enhance the wear resistance of metallic materials, thus extending the lifespan of products[14].

Today, there are numerous methods developed to coat the implant material. These include chemical vapor deposition (CVD), physical vapor deposition (PVD), ion beam, laser, plasma spray, vacuum plasma, HVOF (high velocity oxygen fuel thermal spray process), sol gel immersion and EPD[15-21]. Physical vapor deposition (PVD) techniques are used extensively to deposit a wide range of materials on a number of substrates. The general classification of PVD techniques is made according to the methods used to evaporate the target (material to be deposited)[14]. Titanium nitride-based coatings are mostly deposited by magnetron sputtering, cathodic-arc and pulsed laser deposition techniques[14]. DC reactive magnetron sputtering from an elemental target is a popular technique that can produce films with controllable stoichiometry and composition at high deposition rates and on an industrial scale[14].

In this study, wear behaviors and surface properties of Grade 5(Ti6Al4V) alloys, which are getting more and more important in the production of biomedical materials, have been investigated in dry conditions as a function of load and sliding rate parameters with use of wear test instrument. Then TiN, TiAlN, TiCN coated alloys by reactive magnetron sputtering were subjected to wear tests under the same conditions. The wear losses and wear trace widths of coated and uncoated Ti6Al4V alloys were determined after wear test. The results demonstrated that a significant improvement in wear resistance of the alloy with the coating is provided and that the TiN coated Ti6Al4V alloy is more resistant to wear than the uncoated Ti6Al4V and other coating types.

2. Materials and Methods

2.1. Sample preparation and Coating Method

The samples were prepared from the base material Ti6Al4V (grade 5). The chemical composition of the material is given in Table 1. Ti6Al4V alloy developed in 1954 is consumed 75-85% in all titanium alloys due to its heat resistance, strength, flexibility, toughness, workability, weldability, corrosion resistance and biocompatibility[11-13]. Test specimens were cut out of Ti6Al4V plate and prepared in sizes of 20x65x3 mm. Prior to coating, the substrates were ultrasonically cleaned in alcohol and in acetone for 15 min each, rinsed in distilled water and dried.

| Ti | N   | Fe  | Al  | V  | C  |
|----|-----|-----|-----|----|----|
| Bal.| 0.007 | 0.06 | 6.11 | 4  | 0.01 |

In this study, TiN, TiAlN, TiCN coatings were made with reactive magnetron sputtering method. The system has a stainless steel vacuum chamber (600 mm in diameter and 800 mm in high) and two unbalanced planar magnetrons powered by two independent 12-kWDC generator. Sputtering is basically the removal of atomized material from a solid by energetic bombardment of its surface layer which is dependent on the exchange of momentum. The high energy particles used are usually those of a heavy inert or reactive gas (argon, the most commonly used inert gas) or the coating material forms a positive ion[22]. The sputtering material is thrown in an atomic state from the coating material which is called the target. The base material is placed in front of the target to interrupt the flow of sputtered atoms. Magnetron sputtering is a coating technique that is used to produce thin films with magnets placed behind the target in order to limit the plasma. The film layers having different properties are obtained by changing the deposition parameter and the target material[22,23]. Figure 1 shows the principle of the magnetron sputtering method[22,23].
The test specimens were divided into four groups with uncoated and coated. Then the substrates to be coated are suspended in the middle holders and rotated during coating as shown in Figure 1.a.

As the coating process parameters, 5000 W target power, 80 V bias voltage was used in the experiment. The coating process applied to Ti6Al4V and the silicon wafers was conducted as follows: A pressure of 5 mtorr Ar (~25 sccm) and target power of 4500 W were used for about 5 minutes to clean the target. Then a pressure of 5 mtorr, a target voltage of 150 W and DC voltage of 750 V were used for about 25 minutes to clean the substrate. In order to improve adhesion to the substrate, first of all, the Ti coating was applied at a target power of 4000 W and 15 sccm argon flows for 10 minutes and then the other coating was applied using a target power of 5000 W, -80 V bias voltage and argon + N₂ atmosphere in the coating process. TiN, TiAIN and TiCN coatings were applied for 3 hours during the coating experiment.

2.2. Wear Tests

The wear tests of the uncoated Ti6Al4V alloys and coated samples were performed on a wear device as shown Figure 2.a. In the wear tests, Plint's TE 53 SLIM multi-purpose friction and wear test device was used.

The wear behaviours of TiN, TiAIN, TiCN coated by PVD-reactive magnetron sputtering and uncoated Ti6Al4V samples were investigated in a wear tester adapted to pin-on-ring system (ASTM G-77) (Fig. 2.a and Fig. 2.b). DIN 100Cr6 material with 26 mm diameter and 5 mm height(bearing outer ring) was used as wearing part in the wear tests. Its hardness is 61 RC and surface roughness Rₐ.
0.12 μm. Counter wearing part material composition is as follows: C 0.99%, Mn 0.38%, Cr 1.42%, Mo 0.02% and Fe balance. The experiments were carried out at room temperature under dry friction conditions using constant sliding speed (0.5 m/s and 0.9 m/s) and normal load (5, 15 and 30 N) were used as variable parameters. The test time was stable at 15 min.

3. Experimental Results and Discussion

3.1. Coating Characterization

In this study, TiN, TiAlN, TiCN coatings was made with reactive magnetron sputtering method. Before coating, strength and hardness of all samples were increased by plasma nitriding at 25 °C in an atmosphere of 25% Ar + 75% N2 for 1 hour at 650 °C. The hardness of the Ti6Al4V samples were measured under 100 g load by Struers microhardness device before and after plasma nitriding. The hardness of the untreated Ti6Al4V alloy is 384 HV (Vickers hardness) and has an average hardness value of 592 HV after plasma nitriding. After coating, the hardness of TiN, TiAlN, TiCN were measured by CSEM nanohardness tester using a square-based diamond Vickers tip. The hardness values of the coated samples with thicknesses of average 2 micrometers were found to be in the range of 3500-1050 Hv. hardness values were measured approximately 3500 HV for TiN, 1960 HV for TiAlN and 1050 HV for TiCN, respectively.

The surface roughness values were measured in the test specimens by Mitutoyo Surftest roughness device. The measured average surface roughness values of samples before and after coating are shown in Table-2.

| Step no | Ti6Al4V | TiN   | TiCN   | TiAlN   |
|---------|---------|-------|--------|---------|
| 1       | 0.31    | 0.19  | 0.18   | 0.55    |
| 2       | 0.54    | 0.66  | 0.26   | 0.51    |
| 3       | 0.38    | 0.56  | 0.21   | 0.24    |
| 4       | 0.52    | 0.47  | 0.17   | 0.30    |
| Average values | 0.44 | 0.47  | 0.21   | 0.40    |

As shown in figure 3, AFM analyzes to measure surface roughness were also performed and the results were in agreement. The AFM images also show that TiCN has the lowest surface roughness.

Figure 3. AFM images a)Ti6Al4V, b)TiAlN, c) TiCN, d) TiN
The coating thicknesses were measured from silicon wafer cross-sections by SEM analysis. As shown in figure 4, the thicknesses of the coatings on the silicon wafer are very stable. The thicknesses were about average 2 µm. The coating exhibited columnar crystal structure [24].

![Figure 4. Cross sectional SEM image for the TiCN coating thickness](image)

3.2. Results of Wear Test

Before and after the wear test, each specimen and wearing part were cleaned with alcohol, the weight loss of the specimen and wearing part after the test and the wear track widths on the samples and the average coefficients of friction in steady-state sliding regime were determined. In the pin-on-ring wear tests, experiments were carried out using 24 samples.

A sliding distance depend on velocity and time. Friction forces ($F_s$) depending on sliding distance were recorded using Picolog (Data Logger) in the wear tests. The friction force was found from the steady state friction zone as shown in the figure 5 for every experiment. In the literature, similarly, TiAlN showed a long-running in process and a high steady state friction coefficient [14].

![Figure 5. The friction force from the the steady state friction zone for TiAlN.](image)

To calculate the friction coefficient in the wear test, the equation 1 was used. In the literature the change of friction coefficient with time during sliding abrasion was obtained [24]. The friction coefficient can be divided into an adhesion component and a deformation component, which result from the adhesion force and plastic deformation force, respectively[24].

$$\mu = \frac{F_t}{F_n}$$  

(1)
Where; $\mu$ is friction coefficient, $F_n$ is normal load, $F_t$ is friction force (the graphical value).

According to the results of the wear test, the weight loss, wear track widths, coefficient of friction of the samples depending on the test parameters are given in Table 3.

Table 3. The influence of the sliding rate and load on wear behaviour.

| Materials | Sample no | Speed (m/s)$^1$ | Load [N] | Time (min) | Weight loss (mg) | Wear track (mm) | Frictional coefficient $\mu$ |
|-----------|-----------|-----------------|----------|------------|------------------|-----------------|---------------------------|
| Ti6Al4V   | 1         | 0.5             | 5        | 15         | 2.1              | 3.360           | 0.399                     |
|           | 2         | 0.9             | 5        | 15         | 3.7              | 3.828           | 0.216                     |
|           | 3         | 0.5             | 15       | 15         | 4.6              | 4.095           | 0.177                     |
|           | 4         | 0.9             | 15       | 15         | 4.9              | 4.240           | 0.133                     |
|           | 5         | 0.5             | 30       | 15         | 6.8              | 4.525           | 0.073                     |
|           | 6         | 0.9             | 30       | 15         |                  |                 |                           |
| TiN       | 1         | 0.5             | 5        | 15         | 0.2              | 0.610           | 0.502                     |
|           | 2         | 0.9             | 5        | 15         | 0.2              | 0.680           | 0.749                     |
|           | 3         | 0.5             | 15       | 15         | 0.3              | 0.760           | 0.463                     |
|           | 4         | 0.9             | 15       | 15         | 0.4              | 0.897           | 0.389                     |
|           | 5         | 0.5             | 30       | 15         | 0.5              | 0.800           | 0.336                     |
|           | 6         | 0.9             | 30       | 15         | 0.7              | 1.508           | 0.314                     |
| TiCN      | 1         | 0.5             | 5        | 15         | 0.3              | 0.679           | 0.702                     |
|           | 2         | 0.9             | 5        | 15         | 0.6              | 1.025           | 0.591                     |
|           | 3         | 0.5             | 15       | 15         | 0.4              | 2.348           | 0.363                     |
|           | 4         | 0.9             | 15       | 15         | 0.7              | 2.815           | 0.346                     |
|           | 5         | 0.5             | 30       | 15         | 2.2              | 3.683           | 0.225                     |
|           | 6         | 0.9             | 30       | 15         | 8.5              | 4.468           | 0.160                     |
| TiAlN     | 1         | 0.5             | 5        | 15         | 0.2              | 0.856           | 0.690                     |
|           | 2         | 0.9             | 5        | 15         | 0.3              | 0.970           | 0.556                     |
|           | 3         | 0.5             | 15       | 15         | 0.5              | 0.707           | 0.331                     |
|           | 4         | 0.9             | 15       | 15         | 1.9              | 3.710           | 0.235                     |
|           | 5         | 0.5             | 30       | 15         | 3.1              | 3.725           | 0.212                     |
|           | 6         | 0.9             | 30       | 15         | 7.1              | 4.423           | 0.147                     |

In order to understand the variation in frictional coefficient with load, tests were carried out at a sliding rate, a speed of 0.5 m/s, and loads in the range 5-30 N under dry friction conditions. During the tests, the friction forces were continuously recorded throughout the test by a multichannel recorder. Steady state sliding regime average friction coefficients were determined. When friction coefficients are examined in Table 3, it is seen that the friction coefficient values decrease as the sliding rate and load increases. As shown in Figure 6,7 normal load - speed, normal load - friction coefficient graphs were drawn.

It has been studied the wear of coated Ti6Al4V and found that oxidative wear was prevalent under low normal loads. Because of the increase in temperature with friction, it causes oxidation. Since the Ti alloy has the ability to passivate, the situation is similar for uncoated alloys. Once the normal load reached a critical value, the coefficient of friction reduced [25,26].
The high hardness and adhesion strength of the coatings improve the wear resistance [24]. So, the contact between pin and ring continues as metal-coating. The general contact situation changes with time.

Figure 6. The variation in coefficient of friction with load. (0.5 m/s sliding rate)

Figure 7. The variation in coefficient of friction with load. (0.9 m/s sliding rate)

TiCN and TiAlN have a lower coefficient of friction. The coefficient of friction is proportional to the surface roughness. As shown in Figure 8-9, the surface roughness values of TiAIN and TiCN coatings are low. Although the roughness of the uncoated alloy is higher, the coefficient of friction is lower. The reason for this is based on the oxide layer developing on the surface due to passivation. Figure 9 shows that as the sliding rate increases, the roughness becomes even smaller. The sliding rate promotes oxidation as it increases the temperature. When examined in the literature, it is seen that this is due to the increase of the oxidation together with the increase of the friction heat, and the oxide layer is caused by a kind of lubricant effect [14]. The friction coefficient of TiN was higher than that of TiCN while its wear rate was lower. This indicates that the latter coating can perform as a wear resistant coating at high temperatures [14,25].

Figure 8. The variation in coefficient of friction with surface roughness (0.5 m/s sliding rate)
All of the experiments were carried out on the same conditions, with the use of a separate wearing part for each experiment. Weight loss and wear track widths measurements were used to as a measure of wear. Weight loss was measured with sensitive scale (1/10000). Wear track widths were determined by SEM microscopy for each experiment as shown in Figure 10. Measurements in x and y directions were taken and the average was used as the width of wear track.

When the weight loss is examined according to the test parameters, weight loss increases with increasing load and sliding rate. However, the weight loss of the uncoated samples is higher than the weight loss of the coated samples. The lowest wear loss was observed in TiN. The lowest value among the wear track widths given in Table 3 and Figure 11-12 was seen on the TiN coating. After the abrasion test, surface scans and EDX analysis were performed with Scanning Electron Microscope (SEM). The EDX analyzes obtained from the coated specimens show that the oxidation of the coating is due to friction in the wear zone. This result is supported by the optical microscope images of the wear tracks. In the literature wear analyzes show that wear on Ti-based coatings results from the
formation of titanium oxide. Same time the small abrasive particles separated from the coating by the influence of the friction can reveal the sliding wear mechanism [14,26,27].

![Figure 11](image1.png)  ![Figure 12](image2.png)

**Figure 11**. The variation in wear track with load. (0.5 m/s sliding rate)  **Figure 12**. The variation in wear track with load. (0.9 m/s sliding rate)

It is seen that when the values are compared, there is an increase in the track widths depending on the load and sliding rate. Although it is determined that there is a large difference between uncoated specimens and coated specimens at low loads, this difference is reduced as the load increases. This is also related to the friction coefficient. At higher loads, the friction coefficient decreases. The lowest wear rate achieved in the TiN coating. This result was also proportional to the high hardness of the TiN coatings. TiCN and TiAlN showed low wear trace widths, which is consistent with the friction coefficient values. Furthermore, the coating hardness of the samples directly affects the wear resistance[14,26,27]. The samples with a higher coating hardness showed better wear resistance in this study.

When SEM photo images are examined, it is seen that the depth of the tracks increases in the wear area as the load and sliding rate increases. Wear track images obtained from TiAlN coated samples and wear test parameters are seen on the SEM image in Figure 13.

![Figure 13](image3.png)

**Figure 13**. The wear track images of TiAlN coated samples
Depending on the direction of wear, abrasive and adhesive wear mechanisms were observed as shown in the Figure 13 a-b-c. Abrasive wear is more effective. Figure 14 shows wear losses depending on load and speed parameters. The wear loss increases as the load and speed increase, while the lowest wear loss is detected in the TiN coating. It is clear that the coating is effective for increasing the wear resistance of the alloy. Moreover, TiN was the best choice for applications where the predominant wear mechanism is abrasive wear[14,24,28].

![Figure 14](image)

**Figure 14.** The variation in wear loss with load and speed

4. Conclusions

TiAIN, TiN, TiCN coating was deposited on Ti6Al4V alloy. Wear tests were performed at room temperature and in dry conditions. When samples are compared in terms of wear losses, it is shown that the losses in coated specimens are lower than those of uncoated specimens.

The least surface roughness between the coatings is TiCN coating. The main cause of this result is the TiC( the lubricating effect) formed at the surface of the material by changing the gas flows during the coating. When the values obtained are compared, the order of average surface roughness values of the samples is in the order of TiN> Ti6Al4V> TiAIN> TiCN.

It was determined that the wear widths on the samples were homogeneous and almost parallel to each other. Therefore; the widths of the wear track are taken as a measure of the amount of wear in the specimens. 30N and 0.9 m / s test parameters are used in practice; track widths respectively; Ti6Al4V - 4,53 mm> TiCN - 4,47 mm> TiAIN - 4,42 mm> TiN - 1,51 mm.

Wear track widths of the samples are increasing with increasing load. In uncoated samples at the same load values, the track width values were larger than those of the coated ones. This suggests that the coated samples have a higher wear resistance value. when the trace width and weight loss are taken into consideration, the best abrasion performance is TiN coating and then TiAIN and TiCN in order. The values of the friction coefficient; TiN, TiAIN and TiCN coated specimens were found to be lower in the uncoated samples at a normal load of 30N and a speed of 0.9 m / s. When all samples were examined, it was determined that the average friction coefficient values at 30 N normal load and 0.9 m/ s speed were TiN> TiCN> TiAIN> Ti6Al4V.
Acknowledgements

The authors would like to thank the Scientific Research Units at Erciyes University for their contribution and support (Project No: FBY 09-852).

References

1. Jackson M.J., Ahmed W., Titanium and Titanium Alloy Applications in Medicine, Springer US., 533-576, 2007.

2. He L., Mai Y., Chen Z., Fabrication and Characterization of Nanometer CaP (Aggregate)/Al2O3 Composite Coatings on Titanium, Materials Science and Engineering, A 367, 51-56, 2004.

3. Yang D., Liu C., Liu X., Qi M., Lin G., EIS Diagnosis on The Corrosion Behavior of TiN Coated NiTi Surgical Alloy, Current Applied Physics, vol.5, 417–421, 2005.

4. Galante J.O., Lemons J., Spector M., Wilson P.D., Wright T.M., “The Biologic Effect of Implant Materials” Journal of Orthopaedic Research, 9, s 760-775, 1991.

5. Paschoal A.L., Vanâncio E.C., Canale L.C.F., Silva, O.L., Huerta-Vılca D., Motheo A.J., “Metallic Biomaterials TiN-Coated: Corrosion Analysis and Biocompatibility.” Artificial Organs, 27 (5), s 461–464, 2003.

6. Peters, M., Hemptenmacher, J., Kumpfert, J., Leyens, C., Structure and Properties of Titanium and Titanium Alloys, DLR – German Aerospace Center, Cologne, 2003.

7. Leyens, C. and Peters, M., Titanium and Titanium Alloys: Fundamentals and Applications, Wiley-VCH, Weinheim, 2003.

8. Danışman Ş., Savaş S., The Effect of Ceramic Coatings on Corrosion and Wear Behaviour, Journal of the Balkan Tribological Association, Vol.12, No.1, pp 104-113, 2006.

9. Danışman Ş., Savaş S., Işık G., Bendeş O., Özbekler A., Wear Resistant Hard Ceramic Coatings Used in Biomedical Applications, 4 th National Biomechanics Congress, Erzurum, 2008.

10. Probst J., Gbureck U., Thull R., “Binary Nitride and Oxynitride PVD Coatings on Titanium for biomedical Applications.” Surface and Coatings Technology, 148, s 226-233, 2001.

11. Harman M.K., Banks S.A., Hodge W.A., “Wear Analysis of a Retrieved Hip Implant with Titanium Nitride Coating.” The Journal of Arthroplasty, Vol. 12 No. 8, s 938-945, 1997.

12. Vadraj A., Kamaraj M., “Effect of Surface Treatments on Fretting Fatigue Damage of Biomedical Titanium Alloys.” Tribology International, 40, s 82-88, 2007.

13. Vadraj A., Kamaraj M., “Characterization of Fretting Fatigue Damage of PVD TiN Coated Biomedical Titanium Alloys.” Surface and Coatings Technology, 200, s 4538-4542, 2006.

14. Santecchia E., Hamouda A.M.S., Zalnezhad E., Musharavati F., Cabibbec M., Spigarelli S., Wear resistance investigation of titanium nitride-based coatings, Ceramics International vol.41, 10349–10379, 2015. REVIEW

15. Ceschini L., Lanzoni E., Martini C., Prandstraller D. and Sambogna G., “Comparison of Dry Sliding Friction and Wear of Ti6Al4V Alloy Treated by Plasma Electrolytic Oxidation and PVD Coating”, Wear, Vol. 264, pp. 86-95, (2008).

16. Maurer A.M., Brown S.A., Payer J.H., Merritt K., Kawalej J.S., “Reduction of Fretting Corrosion of Ti-6Al-4V by Various Surface Treatments.” Journal of Orthopaedic Research,11, s 865-873, 1993.
17. Holland L., “Substrate Treatment and Film Deposition in Ionized and Activated Gas.” Thin Solid Films, 27, s 185-203, 1975.

18. Wilson R.W, Terry, L.E., “Application of High-rate ExB or Magnetron Sputtering in the Metallization of Semiconductor Devices.” J. Vac. Sci. Technol., 13(1), s 157-164, 1976.

19. Schiller S., Hessig, U., “The Role of Plasmatron-Magnetron Systems in Physical Vapour Deposition Techniques.” Thin Solid Films, 54, s 33-47, 1978.

20. Grzesik, W., Zalisz, Z., Nieslony, P., Friction and Wear Testing of Multilayer Coatings on Carbide Substrates for Dry Machining Applications, Surface and Coatings Technology, 155, 37-45, 2002.

21. Barshilia H.C., Yogesh K., Rajam K.S. “Deposition of TiAlN coatings using reactive bipolar-pulsed direct current unbalanced magnetron sputtering”, Vacuum, 83, 427-434, (2009).

22. Danisman K., Danisman Ş., Savaş S., Dalkiran I., "Modelling of the Hysteresis Effect of Target Voltage in Reactive Magnetron Sputtering Process by Using Neural Networks", Surface and Coatings Technology, vol.204, pp.604-614, December 2009

23. Savaş S., Danışman Ş., "Multipass Sliding Wear Behavior of TiAlN Coatings Using a Spherical Indenter: Effect of Coating Parameters and Duplex Treatment", Tribology Transactions, vol.57, pp.242-255, March 2014

24. W.Cui, G.Qin, J.Duan, H.Wang, “A graded nano-TiN coating on biomedical Ti alloy: Low friction coefficient, good bonding and biocompatibility”, Materials Science and Engineering vol.C71, pp.520-528, 2017.

25. Lau K.H., Li K.Y., “Correlation between Adhesion and Wear Behaviour of Commercial Carbon Based Coatings”, Tribology International, 39, 115-123, (2006).

26. Wei, M. X. Wang, S. Q., Cui, X. H., and Chen, K. M., Characteristics of extrusive wear and transition of wear mechanisms in elevated-temperature, Tribology Transactions, 53, 888–896, 2010.

27. Luo K., Hovsepian P.Eh., Lewis D.B., Münz W.D., Kok Y.N., Kokrem et al., “Tribological properties of unbalanced magnetron sputtered nano-scale multilayer coatings TiAlN/VN and TiAlCrYN deposited on plasma nitrided steels”, Surface and Coatings Technology, 193, 39-45 (2005).

28. Mezlini S., et al., “Effect of Indenter Geometry and Relationship Between Abrasive Wear and Hardness in Early Stage of Repetitive Sliding”, Wear, 260, 412-421, (2006).