Comparison of the mechanical properties and electrochemical behavior of TiN and CrN single-layer and CrN/TiN multi-layer coatings deposited by PVD method on a dental alloy

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Abstract
Metallic materials used in medicine and dentistry should have high corrosion resistance and high biocompatibility. In this study, the influence of TiN, CrN and TiN/CrN layers on the hardness, surface roughness, and the corrosion resistance of Ni–Cr ceramic dental alloys in an artificial saliva environment (pH = 8) were evaluated. Ni–Cr dental alloys were produced by lost-wax casting and the TiN, CrN and TiN/CrN nanolayer coatings were deposited by means of arc-physical vapor deposition method. The microstructural characterization of selected alloys was performed before and after electrochemical tests, using scanning electron microscopy, energy dispersion spectroscopy, and x-ray diffraction. The surface roughness of the alloys was investigated by Profilometer. Surface characterization of the passive layer formed on the coated and uncoated Ni–Cr dental alloys in artificial saliva was studied using impedance spectroscopy measurement. The results showed that hardness of the ceramic-coated materials is noticeably greater than that of the uncoated substrate. Also, polarization and impedance spectroscopy measurements revealed that CrN coating has an exceptionally high polarization resistance compared to Ni–Cr dental alloy and TiN and TiN/CrN coatings.

1. Introduction

A surface modification aims at improving surface properties of metallic materials [1]. It might be useful to use this dental alloy modification with surface layering materials so that corrosion-related problems can be prevented [2, 3]. There are different applicable coatings such as solids, liquids, or gases including the formation of a monolayer, or even more, to cover the original surface [4], which is usually referred to as the substrate. There is an opportunity to utilize combinations of coatings so that certain goals can be achieved. A coating type, for instance, can be used to improve attaching another coating to a certain substrate. Different types of coating are used, depending on the characteristics of a coating, for improving surface properties such as corrosion resistance, biological interaction, wear resistance, scratch resistance, appearance, adhesion, and wettability. As for different coatings, the coating interaction with the substrate and the surrounding environment would be the main challenge [4]. The process in which the materials are evaporated or sputtered is called physical vapor deposition (PVD) which helps forming ions, molecules, or atoms, to be then moved to the substrate surface in such a way that a thin film is formed on the substrate. The usual properties of such a process are multi-component layers, the choice variety of substrate and coating materials, strong adhesion, low substrate temperature, high coating density [5, 6]. In the field of biomaterials, coating techniques like PVD are getting interest more and more [3]. They are also capable of increasing the hardness along with outstanding surface finishing, reducing, as a result, the wear rate and friction [7, 8]. Nevertheless, there is only one limitation about coatings represented by their adhesion to the substrate permitting chemical bonds to be interacted between the
layers [7]. There are a lot of biocompatibility tests (including hemolysis, irritation tests, systemic toxicity, sensitization, genotoxicity, and cytotoxicity) described by Pellman and fulfilled for varied coatings of PVD such as TiN, ZrN, CrN, TiAlN, and AlTiN. All of them seem appropriate for making a contact with blood tissue, skin, and bone. Furthermore, CrN as well as TiN are highly stable during chemical autoclaving and steam sterilization. Consequently, they are capable of improving certain properties of medical devices, especially the mechanical and the anti-corrosive ones, making their surfaces separated from what is regarded as aggressive environments of human physiological fluids and other chemicals, and, as a result, their life-time might be extended [9]. Those coatings are classified into two basic classes. One of them is amorphous carbon coating, while the other one is transition metal nitride coatings, such as TiN, CrN, and TiAlN [10–12]. Besides, the used alloys have to stand against humidity, pH changes from (2–11), which happens during the chewing process inside the mouth, and finally the change in temperature inside the oral cavity changing from (0 up to 70 °C).

Unluckily, foods are not of the same categories and, as a result, have different pH levels [13]. Nanotechnology is driving newer requirements and demands for having better performance of existing materials since it paves the way for metal surface modifications in response to demands on the metal surface for their bio-medical uses [6]. Being hard and versatile ceramic, TiN is known to be crystallized in the B1 NaCl structure. It is usually found as a solid solution with a N2 concentration ranging from 37.5 to 50%. TiN has very good properties regarding wear and corrosion resistance, and it is widely used in cutting tools in order for their lifespan to be increased. Titanium nitride has a combination of high ductility and hardness in addition to biocompatible properties, resulting in its uses medically especially for implants such as dental prosthesis and orthopedic. PVD is a group of widely used techniques to get thin films. In order to be deposited, the material is evaporated, during a PVD process, from the source (target), usually a solid or liquid, and is carried to the substrate in a form of plasma, where it condenses [14]. In comparison to other coatings, chromium nitride coating, which is obtained by cathodic arc evaporation (CAE), has a superior resistance to corrosion and abrasion. Also, when compared to other coatings, defects present in the coating may degrade its properties with time. Due to establishing the electrochemical potential difference between the coating and the substrate, the corrosion processes adopt and after localizing form and run within the defects [15].

The creation of multilayer (nanolayer) coatings and films for a variety of functional purposes is regarded as a rapidly-developing area of nanotechnology. There is a remarkable interest in multilayered nanostructured coatings and films, in which exothermic reactions between the components of the layered systems propagate freely in a heating regime because of the heat generation during reactions with outer heating sources [16]. This study aims at investigating the possibility of achieving better mechanical as well as electrochemical properties in the Ni-Cr dental alloy with TiN, CrN and TiN/CrN nanolayer deposited by CAE technique in artificial saliva environment.

2. Materials and methods

2.1. Substrate preparation and coating process

One sheet of modeling wax (18.7 cm in length, 8.5 cm in width and 1.5 mm in thickness, Cavex, Holland) was punched with a copper ring (locally made, 25 mm in diameter) as mold. The chemical composition of Ni-Cr alloy (Kera ®NH, Germany) include (Ni 58.48%, Cr 26.85%, Mo 12.72, Si 1.72% and other <0.1%). Casting can be described as a method used for producing a shaped piece made from a metallic material [17]. The wax patterns were spruced centrally and vertically inside the rubber ring (Each 4 samples were sprued and invested in one casting ring using a phosphate-bonded investment). The burnout step was carried out according to manufacturer’s instruction for temperature and timing of (Kera ®NH, Germany). The casting of Ni-Cr was carried out by the induction casting machine (Ducatron) at casting temperature (1310 °C) according to the manufacturer’s instruction of alloy. Then all sprues would be sectioned by the separating mounted disc on a laboratory hand piece. All specimens were cleaned ultrasonically with distilled water to remove any debris and residues of Al2O3 powder. All of the samples were wet grinded with SiC paper from 60–2000 grits in order for the substrates to be prepared and, after that, utilized a diamond past for polishing, then cleaned using acetone and distilled water in an ultra-sonic cleaner device and dried at room temperature. Samples were checked using a metal caliper instrument for correcting the dimension for each sample (1.5 mm) thickness and (25 mm) diameter. Samples were put in desiccator before the experiments so as to prevent contamination [18].

PVD technique is composed of atomic deposition procedures in which a material is vaporized from liquid or solid sources as molecules or even atoms, and then moved as vapor through a vacuum or low-pressure gaseous (plasma) environment to a substrate, where it eventually condenses. Such a technique is seen to be appropriate for the deposition of films ranging from a few nanometers up to thousands of nanometers [1]. TiN and CrN with the B1 structure are simultaneously formed. The specimen rotating stage was stopped from time to time to expose specimens to Ti and Cr targets, respectively, for pre-determined time periods to deposit alternate TiN
and CrN layers of equal thickness. Table 1 lists the details of PVD processing parameters in this study. Coatings were deposited by CAE method (DS&CA601, Yarnikan saleh, Iran). The coatings’ thickness has been measured as 1.8 ± 0.2 μm (figure 1), respectively on the samples. A multilayer by TiN/CrN was formed under the same conditions.

### 2.2. Coating characterization

The surface features of biomaterials play a basic role in being interacting with biological systems [19]. TiN/CrN multilayer, which comprises changing nanometer scale of TiN and CrN layers, were deposited by a PVD technique and characterized using scanning electron microscopy (SEM), x-ray diffraction (XRD), and energy dispersion spectroscopy (EDS) analysis. The characterization and morphology of the coated samples were studied by means of a SEM (MIRA3, TESCAN, Czech). The purpose of implementing XRD experiments was to complement the measurements of SEM for identifying the phases present in the microstructure of specimens, whether coated or uncoated. The XRD measurements were performed by an XRD (PANalytical, and Philips PW-1730), and the data processing was carried out using X’Pert High Score Software. The diffraction angle measurement ranged 2θ from 20°–80°, using the Cu–Kα radiation. For the coatings thickness determination, the cross-sectional microstructures of the coatings were investigated applying field emission scanning electron microscopy (FESEM, MIRA3, TESCAN, Czech) with an accelerating voltage of 15.0 kV equipped with EDS (SAMX, France).

### 2.3. Preparation of the artificial saliva

Smith and Morton strongly believe that saliva acidity or alkalinity relies on the flow rate, but the pH is usually within the range 6.2–8.0 [20]. The electrolyte reference used was modified Fusayama artificial saliva [21], which closely resembles natural saliva, the composition and concentration of the used artificial saliva (modified Fusayama formulation): NaCl 0.4 g L⁻¹, KCl 0.4 g L⁻¹, CaCl₂ 2H₂O 0.795 g L⁻¹, NaH₂PO₄·H₂O 0.690 g L⁻¹, Na₂S·9H₂O 0.005 g L⁻¹, Urea 1.0 g L⁻¹, and KSCN 0.3 g L⁻¹ [22]. All the mentioned materials are dissolved in distilled water and the pH value has been modified at the preferred value utilizing NaOH (pH = 8).

### 2.4. Surface roughness measurement

A surface analyzer (ROUGHNESS TESTER PCE RT 2200) was used to evaluate the roughness of the uncoated and coated groups, so that the ΔRa (roughness differences) can be obtained. The stylus was moved across the specimen surface, and three lines were recorded noting that a distance between each scanning line was (1 mm) [23]. Being considered as the mean roughness of the sample, the mean Ra was measured from those three lines, and the resolution of the recorded data was ±20 μm.

### 2.5. Vickers hardness measurement

Vickers harness test (Microhardness measurements) has been used for measuring the hardness of the surface, using an indenter point in the shape of a square-based pyramid (the 136° pyramidal diamond indenter creating a square indent was used) [24]. Vickers hardness number was measured using 500 g load at 15 s loading time by using digital microhardness tester (Buehler, Lake Bluff, Illinois) [25]. Statistical methods have been used in order to analyze and assess the result, the ΔRa and hardness values were undergone to a statistical analysis by least significant difference (LSD) and one-way analysis of variance (ANOVA). These were used in order to accept or reject the statistical hypotheses, using the statistical program SPSS ver. 21.

| Table 1. Lists the details of the PVD processing parameters in this study. |
|-----------------------------|
| **Deposition parameters**   |
| Target (at%) Ti             | (99.95%) |
| Target (at%) Cr             | (99.95%) |
| base pressure (Pa)          | 6.7 × 10⁻³ |
| working pressure (Pa)       | 0.67     |
| substrate bias voltage (V)  | -100     |
| substrate temperature (°C)  | 200      |
| deposition time (s)         | 7200     |
| distance between substrate and target (mm) | 150 |
2.6. Electrochemical measurements
The artificial saliva solution temperature was kept, during the study, at room temperature \[18\]. Some electrochemical tests were carried so that the electrochemical behavior of the samples, whether coated or uncoated, could be studied, so it should be mentioned that all of the experiments were performed by means of an electrochemical cell using three electrodes; Pt (counter electrode), Ag/AgCl (reference electrode), and Ni-Cr dental alloy (working electrode). The experiments were performed by a \( \mu \)Auto lab Type III/FRA2 system controlled by computer equipped with Nova 1.7 software. The determination of the open-circuit potential (OCP), as a function of time was included at the electrochemical measurements. All measurements were done after one hour stabilization at OCP \[26\]. The potentiodynamic polarization (PDP) tests were started after 1 h stabilization of the specimens in the OCP conditions. The measurements have been fulfilled at a 0.001 V s\(^{-1}\) scan rate over a potential ranging from \(-0.25\) V (versus \(E_{corr}\)) up to \(+1.0\) V\(_{Ag/AgCl}\). Also, the electrochemical impedance spectroscopy (EIS) measurements were carried out at the OCP conditions with a step rate of 10 point/decade in the applied frequency range of 100 kHz to 10 mHz by applying an alternating amplitude of 10 mV \[27\].
3. Results and discussion

3.1. Characterization of deposited specimens

The thickness of the layers has been evaluated from the cross section SEM depicted in figure 1. The composition of the TiN coatings is confirmed by the EDS measurements with a ratio of titanium to nitrogen (38.47:61.53). The composition of the CrN coatings is confirmed by the EDS measurements with a ratio of chromium to nitrogen (43.23:56.77), and the chemical composition of the TiN/CrN coatings (components of TiN/CrN nanolayer coating) reaches nearly (54.61 at% of titanium, 35.63 at% of nitrogen, and 9.76 at% of chromium)

Figure 2. EDS line analysis of the coated samples: (a) TiN, (b) CrN, and (d) TiN/CrN.
The EDS specimens line analysis show the inter-diffusion of elements in TiN coating, CrN coating, and TiN/CrN multilayer coating in figure 2. Irregularities of surface are considered as a model for arc evaporation owing to the macro-particles incorporation [28]. Porosity is another surface defect being noticed also in all conditions, whether single layered or a nanolayered one, they could be produced by the nucleation and layer growth that takes place when the incoming molecules or atoms are less strongly attracted to each other than to the substrate, and, thus, an entire layer would be completed before initiating to make a new one, as being reported by other researchers [29]. The XRD patterns of TiN, CrN, and CrN/TiN coatings are shown in figure 3 compared to that of Ni-Cr substrate. The diffraction patterns in this figure show a typical face centered cubic (FCC) polycrystalline structure like B1 type with mixed orientations of (111), (200), (220), and (311) planes for the coatings. A strong (111) preferred orientation is shown by the XRD pattern of the TiN coating, but the preferred orientation for the other patterns is (200) plane.

### 3.2. Hardness and surface roughness properties

The TiN, CrN single layer and TiN/CrN multilayer were prepared in order to study the relationship between mechanical properties and microstructure of coatings by PVD technique. The hardness and elastoplastic characteristics of coatings can be significantly increased by the formation of a nanostructured state in them [30]. The results showed that TiN/CrN multilayer raised the mean hardness strength values followed by CrN single layer and followed by TiN single layer when compared among coated groups, mention in table 2. Three Vickers indentations were conducted for each specimen (uncoated and coated surface), mean and standard deviation was recorded. The mean hardness values of Ni-Cr alloy for all groups are presented in table 2 and figure 4. The source of difference is investigated by further complement analysis of data by using LSD test to examine the difference in pairs of the four groups as shown in table 3 (test show that there are statistically highly significant differences at \( p < 0.01 \)). Figure 5 shows the SEM micrograph regarding a Vickers indenter print on the film surface.
A statistically significant difference of surface roughness of both uncoated and coated specimens was shown by a one-way ANOVA. Significantly higher surface roughness of the nickel chromium for the samples coated with TiN/CrN was also indicated by further analysis by the LSD test. Table 4 and figure 6 present standard deviations of each group and the mean ΔRa. A statistically significant difference in surface roughness of the uncoated sample was shown by a one-way ANOVA data when being compared with coated samples, but no significant difference was found for TiN and TiN/CrN; this is due to the fact that the outer surface of the two

Table 2. Descriptive statistic and ANOVA test for uncoated and coated groups for micro-hardness test.

| Studied groups (Vickers hardness test) | Mean  | SD    | ANOVA test (P-value) |
|---------------------------------------|-------|-------|----------------------|
| Substrate                             | 270.46| 9.608 | P = 0.00 Highly sign. (P < 0.01) |
| TiN                                   | 760.995| 107.401| |
| CrN                                   | 840.968| 76.138| |
| TiN/CrN                               | 949.77| 225.857| |

Table 3. Least significant difference (LSD) test for the Vickers hardness test for coated and uncoated groups.

| Studied groups (Vickers hardness test) | LSD test (P-value) |
|---------------------------------------|-------------------|
| Substrate                             | P = 0.00 Highly sign. (P < 0.01) |
| TiN                                   | P = 0.00 Highly sign. (P < 0.01) |
| CrN                                   | P = 0.00 Highly sign. (P < 0.01) |
| TiN/CrN                               | P = 0.348 Non Sign. (P > 0.05) |
| TiN                                   | P = 0.037 Sign. (P < 0.05) |
| CrN                                   | P = 0.207 Non Sign. (P > 0.05) |

Figure 5. SEM micrograph of Vickers indentation print in substrate, TiN, CrN, and TiN/CrN nanolayer.
groups is the same surface (TiN). LSD test was used to examine the difference in pairs of the four groups as shown in Table 5.

### 3.3. Electrochemical behavior

The surfaces of the alloys were tested using SEM in order for the form of corrosion attack to be identified. Figure 7 shows the SEM images of the substrate, TiN, CrN, and TiN/CrN samples before and after the electrochemical test. These images depicted that no serious defects were noticed within the TiN, CrN, and TiN/CrN nanolayer coating when compared with uncoated surface. The pitting corrosion which is also known as a type and form of localized corrosion on the alloy surface (pitting attacks in the form of spots or pits) on the surface for uncoated alloy.

PDP curves of Ni-Cr dental alloy and TiN, CrN, and TiN/CrN nanolayer coatings in modified Fusayama artificial saliva (pH = 8) are revealed in figure 8. An identical shape is depicted all the plots, with a distinct Tafel behavior, the linear variation of potential is seen as a function of log of current density may be observed in all situations. Similar PDP curves were noticed in solutions such as Ringer’s and Hank’s for CrN and CrCN/CrN coatings deposited using CAE [9]. Moreover, the PDP plots show that passive behavior of CrN coating improved than the Ni-Cr dental alloy, TiN/CrN and TiN coatings. Also, the PDP curves reveal that CrN coating has an exceptional polarization resistance which is considered much higher being compared to the Ni-Cr dental alloy, TiN/CrN and TiN coatings. In other words, a better passive film must have been formed on its surfaces. The

| Table 4. Descriptive statistic and ANOVA test of different groups for surface roughness measurement. |
|-----------------------------------------------|
| Studied groups (surface roughness) | Mean (μm) | SD | ANOVA test (P-value) |
|-----------------------------------------------|
| Substrate | 0.023 | 0.005 | P = 0.00 Highly sign. (P < 0.01) |
| TiN | 0.179 | 0.021 | |
| CrN | 0.118 | 0.007 | |
| TiN/CrN | 0.189 | 0.037 | |

| Table 5. Least significant difference (LSD) test for the surface roughness test for four groups. |
|-----------------------------------------------|
| Studied groups (Surface roughness) | LSD test (P-value) |
|-----------------------------------------------|
| Substrate | TiN | P = 0.00 Highly sign. (P < 0.01) |
| CrN | P = 0.001 Highly sign. (P < 0.01) |
| TiN/CrN | P = 0.00 Highly sign. (P < 0.01) |
| TiN | CrN | P = 0.009 Highly sign. (P < 0.01) |
| TiN/CrN | P = 0.633 Non Sign. (P > 0.05) |
| CrN | TiN/CrN | P = 0.004 Highly sign. (P < 0.01) |
variations of corrosion potential of all samples in modified Fusayama artificial saliva (pH = 8) are shown in table 6 as well as corrosion current densities. Using Tafel extrapolation of the linear part for the cathodic branch back to the corrosion potential, corrosion current density ($i_{corr}$) was calculated with an accuracy of more than...
As can be seen, CrN coating reveals the least corrosion current density compared with other samples. In general, CrN has been characterized having good corrosion resistance as well as chemical stability [9]. Based on the literature analysis, Lee et al. [34] stated there is a higher amount of pinholes present in the TiN layer deposited on rougher surfaces of the substrate. Also indicates that a decrease of the corrosion current density and a shift of the corrosion potential in a positive direction are observed for the purpose of reduced surface roughness of CrN-coated samples.

The results in the present study are supported and in agreement with [28] what they found that one of the best candidates for corrosion resistant coatings is a ceramic thin film. Titanium-based hard films are considered as important as those based on chromium, such as CrN. There are many benefits regarding the films as being represented by high corrosion resistance, low wear rate, and finally low friction coefficient. Also, agree with [35] they reported that new areas of applications will pave the way for improving those characteristics by changing the structure (e.g. multilayered) or the chemical composition (for introducing another element to Cr–N system). Recently, ternary Cr–X–N coatings, where X can be (Al, Ti, Si, O, C) or other elements, have been intensively investigated. Roa and cooperators [36] made not only TiN monolayer and CrN monolayer coatings but also TiN/CrN multilayer coatings by means of multi-source cathodic reaction arc evaporation. The main purpose of using indentation and scratch test was to study the failure mechanism of TiN/CrN coating. Results have shown that multilayer films were higher than the critical load in case of a fault taken place in a single layer coating. Using multilayered, multi-component and nanostructured coatings is increasingly important and it is the master way for having an increase in the preventive properties of industrial products, as well as their hardness strength, wear, and corrosion resistance under different conditions [14].

Figure 8 shows the Nyquist plots of substrate and coated samples in modified Fusayama artificial saliva. Figure 9 shows the Nyquist plots of substrate and coated samples in modified Fusayama artificial saliva (pH = 8). All Nyquist plots reveals imperfect semicircles. As the largest semicircle belongs to CrN monolayer coating, it has the highest total resistance. In order to emulate the measured EIS data, the equivalent electrical circuit shown in figure 10 (with two time constants) was used [37]. Such equivalent electrical circuit was provided best fitting for the EIS data as depicted in figure 9. In this electrical circuit, \( Q_p \) shows the constant phase element of the passive film, \( R_p \) reveals the passive film resistance.

### Table 6. The variations of corrosion potential and corrosion current densities of all samples in modified Fusayama artificial saliva (pH = 8).

| Sample | \( E_{corr} \) (V Ag/AgCl) | \( i_{corr} \) (μA cm\(^{-2}\)) |
|--------|-----------------|-----------------|
| Substrate | −0.351 | 0.041 |
| TiN | −0.280 | 0.024 |
| CrN | −0.293 | 0.003 |
| Multilayer | −0.440 | 0.018 |
Figure 9. Nyquist plots of uncoated and coated Ni-Cr prosthetic dental alloy in modified Fusayama artificial saliva (pH = 8) after: (a) 1 h, (b) 14 days, and (c) 21 days.

$Q_{dl}$ depicts the constant phase element (CPE) of the double layer, $R_{ct}$ is the charge-transfer resistance, and $R_S$ stands for the solution resistance. The variations of the passive film and charge-transfer resistance of substrate, TiN, CrN, and TiN/CrN coatings in modified Fusayama artificial saliva (pH = 8) are shown in table 7. As can be seen, CrN monolayer coating shows the highest passive film and the charge-transfer resistance compared with other samples. Thus, the calculated amount of polarization resistance ($= R_p + R_{ct}$) for this coating (CrN...
monolayer) is the highest, which shows the lowest corrosion current density. These results agree with those obtained by Chen et al [38] who demonstrated that the as-deposited CrN coating showed superior corrosion resistance in NaCl solution. Indeed, the reduction of the corrosion current density and the corrosion potential increase indicate a significant enhancement in the corrosion resistance by a CrN coating deposition (see figure 8). Also, the results agree with those obtained by Santecchia and et al [14] who found that the use of nanostructured coatings is growing in importance and it is a key method for increasing the protective behaviors of different industrial coatings, as well as their hardness and corrosion behavior under the influence of severe working conditions. In addition, Bolton and Hu [39] investigated the corrosive resistance of CrN, TiN, and DLC (three biomedical PVD) coatings at room temperature. Bolton and Hu found improved corrosion resistance for coated specimens, but it has been noted that pit defects continued to expose the substrate to corrosion.

4. Conclusions

Mechanical and electrochemical properties of dental alloy coated by monolayer TiN, CrN and nanolayer TiN/CrN that were deposited by physical vapor deposition technique, were thoroughly investigated. Hardness of the CrN, TiN and TiN/CrN coatings is noticeably greater than that of the uncoated substrate. The results of surface roughness showed that different coating processes resulted in different roughness where the best surface roughness was resulted by CrN coating. The results of potentiodynamic polarization and Nyquist plots show that the passive behavior of CrN coating were more improved than the Ni-Cr dental alloy and other coatings. Moreover, the potentiodynamic polarization and Nyquist plots reveal that CrN monolayer coating has an exceptional polarization resistance which is considered much higher comparing with Ni-Cr dental alloy and other coatings.
References

[1] Arango S, Vargas A P and Garcia C 2013 Coating and surface treatments on orthodontic metallic materials Coatings 3 1–15
[2] Amer M A, Fekry A M and Bahr M A 2017 Effect of Streptococcus mutans on the corrosion behavior of nano-coating Ni-Cr dental alloy Int. J. Electrochem. Sci. 12
[3] Anselme K, Davidson P, Popa A, Giazon M, Liley M and Ploux L 2010 The interaction of cells and bacteria with surfaces structured at the nanometre scale Acta Biomater. 6 3824–46
[4] Söderholm K J M 2012 Coatings in dentistry—a review of some basic principles Coatings 2 138–59
[5] Mattox D M 2010 Ion plating and ion beam-assisted deposition Handbook of Physical Vapor Deposition (PVD) Processing (Boston: William Andrew Publishing) 301–31
[6] Mahapatro A 2015 Bio-functional nano-coatings on metallic biomaterials Mater. Sci. Eng. C 55 227–51
[7] Ching H A, Chouhtry D, Nine M J and Abu Osman N A 2014 Effects of surface coating on reducing friction and wear of orthopaedic implants Sci. Technol. Adv. Mater. 15 1–21
[8] Sabih Mansoor N, Fattah-alhosseini A, Shishehian A and Elmkhah H 2019 Corrosion behavior of single and multiplayer coatings deposited on Ni-Cr Dental Alloy by CAE-PVD technique in artificial saliva Analytical and Bioanalytical Electrochemistry 11 304–20
[9] Gilewicz A, Chmielewka P, Murzynski D, Dobruchowska E and Warocholinski B 2016 Corrosion resistance of CrN and CrCN/CrN coatings deposited using cathodic arc evaporation in Ringer’s and Hank’s solutions Surf. Coat. Technol. 299 7–14
[10] Jokar K, Elmkhah H, Fattah-alhosseini A, Babaei K and Zohriastain A 2019 Comparison of the wear and corrosion behavior between CrN and AlCrN coatings deposited by Arc-PVD method Mater. Res. Express 6 116426
[11] Sabih Mansoor N, Fattah-alhosseini A, Shishehian A and Elmkhah H 2019 Tribological properties of different types of coating materials deposited by cathodic arc-evaporation method on Ni-Cr dental alloy Mater. Res. Express 6 056421
[12] Fattah-alhosseini A, Elmkhah H, Babaei K, Imamzadeh O, Ghomi H R and Keshavarz M K 2018 An investigation regarding semiconducting and passive behaviors of coarse- and nano-structured pure Ta in Ringer’s physiological electrolyte: role of anodic passive potential Mater. Res. Express 5 106401
[13] Amer M A, Khiam E and Al-Motaq M 2004 Electrochemical behaviour of recasting Ni-Cr and Co–Cr non-precious dental alloys Corros. Sci. 46 2825–36
[14] Santeccia E, Hamouda A M S, Musharafati F, Zalnezhad E, Cabibbo M and Spigarelli S 2015 Wear resistance investigation of titanium nitride-based coatings Ceramics Int. 41 10349–79
[15] Attarzadeh F R, Elmkhah H and Fattah-alhosseini A 2017 Comparison of the electrochemical behavior of Ti and nano-structured Ti coated AISI 304 stainless steel in strongly acidic solutions Metallurgical and Materials Transactions B 46B 227–36
[16] Lebedev E A, Petrizhik M I, Tyurina M Y, Kiryukhantsev Korneev F V, Tsygankov P A and Rogachev A S 2011 Multilayer nanostructured heat generating coatings: preparation and certification of mechanical and tribological properties Metallurgist 54 9–10
[17] Galo R, Rocha I A, Faría A C, Silveira R R, Ribeiro R F and de Mattos M G C 2014 Influence of the casting processing route on the corrosion behavior of dental alloys Mater. Sci. Eng. C 45 519–23
[18] Rao S B and Chowdhary R 2011 Evaluation on the corrosion of the three Ni-Cr alloys with different composition Int. J. Dentist. 10 1–5
[19] Chang Y, Huang H L, Chen H J, Lai C H and Wen C Y 2014 Antibacterial properties and cytocompatibility of tantalum oxide coatings Surf. Coat. Technol. 259 193–8
[20] Amal A S S, Hussain S and Jalaluddin M A 2015 Preparation of artificial saliva coating Current Breakthrough in Pharmacy Materials and Analyses 6 10
[21] Al-Mashhadani H A Y 2018 Study the effect of Punica Granatum as oral antifungal on the corrosion inhibition of dental amalgam alloy in saliva J. Mater. Environ. Sci. 9 662–71
[22] Liliana P, Elenai S C, Virgil C L, Laurentiu D M and Sorin P 2018 Daniel corrosion behavior of Ni-Cr dental casting alloys Int. J. Electrochem. Sci. 13 410–23
[23] Davi L R, Felipucci D N B, de Souza R F, Bezzon O L, Lovato-Silva C H, Pagnano V O and Paranhos H O 2012 Effect of denture cleansers on metal ion release and surface roughness of denture base materials Braz. Dent. J. 23 587–93
[24] Cortés-Sandoval G, Martínez-Castañón G A, Patiño-Marin N, Martínez-Rodriguez P R and Loyola-Rodriguez J P 2015 Surface roughness and hardness evaluation of some base metal alloys and denture base acrylics used for oral rehabilitation Mater. Letters 144 100–5
[25] Thopengowda N B, Shenoy K, Shankaranarayana R K, Jayaprakash K, Ginigupalli K, Vaddy S B and Prabhhu S 2014 Evaluation of mechanical properties of recast dental base metal alloys for considering their reusability in dentistry and engineering field Archives of Medicine and Health Sciences 2 178–82
[26] Romonić D C, Voico G and Prodana M 2015 Electrochemical behavior of coated and uncoated nonprecious CoCr and NiCr alloys in artificial and natural Salivatin J. Electrochem. Soc. 106935–45
[27] Attarzadeh F R, Attarzadeh N, Vafaiean S and Fattah-alhosseini A 2016 Effect of pH on the electrochemical behavior of Tantalum in borate buffer solutions J. Mater. Eng. Perform. 25 4199–209
[28] Warocholinski B, Gilewicz A, Kulikinski Z and Myśliński P 2008 Arc-evaporated CrN, CrN and CrCN coatings Vacuum 83 715–8
[29] Gallegos-Cantú S, Hernandez-Rodriguez M A L, Garcia-Sanchez E, Juarez-Hernandez A, Hernandez-Sandoval I and Cue-Sampedro R 2015 Tribological study of TiN monolayer and TiN/CrN (nanolayer and superlattice) on Co–Cr alloy Wear 330 439–47
[30] Shitansky D V, Lysatosky I V and Levashov E A 2004 Comparative Investigation of TiSi N–Films Magnetron Sputtered Using Ti5Si3 + Ti and Ti5Si3 + Ti Targets Surf. Coat. Technol. 182 210–20
[31] Burstein G T 2005 A hundred years of Tafel’s equation: 1905–2005 Corros. Sci. 47 2858–70
[32] Anselme K, Davidson P, Popa A, Giazon M, Liley M and Ploux L 2010 The interaction of cells and bacteria with surfaces structured at the nanometre scale Acta Biomater. 6 3824–46
[33] Keshavarz M K and Fattah-alhosseini A 2018 Effect of immersion time on corrosion behavior of single-phase alloy and nanocomposite bismuth telluride-based thermoelectrics in NaCl solution J. Mater. Eng. Perform. 27 3386–93
[34] Lee S C, Ho W Y and Lai F D 1996 Effect of substrate surface roughness on the characteristics of CrN hard films Mater. Chem. Phys. 43 266–73
[35] Gilewiczn A and Warcholinski B 2014 Tribological properties of CrCN/CrN multilayer coatings Trib. Int. 80 34–40
[36] Roa J J, Jiménez-Piqué E and Martínez R 2014 Contact damage and fracture micro mechanism of multilayer TiN/CrN coatings at micro- and nano length scales Thin Solid Films 2 308
[37] Elmkhah H, Abdollah-zadeh A, Mahboubi F, Sabour Rouhaghdam A R and Fattah-alhosseini A 2017 Correlation between the duty cycle and the surface characteristics for the nanostructured titanium aluminum nitride coating deposited by pulsed-DC PACVD technique J. Alloys Comp. 711 530–40
[38] Chen Q, Cao Y, Xie Z, Chen T, Wan Y, Wang H, Gao X, Chen Y, Zhou Y and Guo Y 2017 Tribocorrosion behaviors of CrN coating in 3.5 wt% NaCl solution Thin Solid Films 622 41–7
[39] Bolton J and Hu X 2002 In vitro corrosion testing of PVD coatings applied to a surgical grade Co–Cr–Mo alloy J. Mater. Sci., Mater. Med. 13 567–74