

Electron beam modification (EBM)

Subjects: [Electrochemistry](#) | [Cell & Tissue Engineering](#)

Contributor: Maria Nikolova

Vacuum cathodic arc TiN coatings with overlaying TiO₂ film were deposited on polished and surface roughened by electron beam modification (EBM) Ti6Al4V alloy. The substrate microtopography consisted of long grooves formed by the liner scan of the electron beam with appropriate frequencies (500 (AR500) and 850 (AR850) Hz). EBM transformed the $\alpha + \beta$ Ti6Al4V mixed structure into a single α' -martensite phase. The gradient TiN/TiO₂ films deposited on mechanically polished (AR) and EBM (AR500 and AR850) alloys share the same surface chemistry and composition (almost stoichiometric TiN, anatase and rutile in different ratios) but exhibit different topographies (S_a equal to approximately 0.62, 1.73, and 1.08 μm , respectively) over areas of $50 \times 50 \mu\text{m}$. Although the nanohardness of the coatings on AR500 and AR850 alloy (approximately 10.45 and 9.02 GPa, respectively) was lower than that measured on the film deposited on AR alloy (about 13.05 GPa), the hybrid surface treatment offered improvement in critical adhesive loads, coefficient of friction, and wear-resistance of the surface. In phosphate buffer saline, all coated samples showed low corrosion potentials and passivation current densities, confirming their good corrosion protection. The coated EBM samples cultured with human osteoblast-like MG63 cells demonstrated increased cell attachment, viability, and bone mineralization activity especially for the AR500-coated alloy, compared to uncoated polished alloy. The results underline the synergetic effect between the sub-micron structure and composition of TiN/TiO₂ coating and microarchitecture obtained by EBM.

surface patterning

electron beam modification

roughness

TiN/TiO₂ coating

osteogenic cells

1. Introduction

The surface characteristics of the implant material predetermine how the biomolecules absorb to the surface ^[1]. The adhesion proteins such as extracellular matrix proteins, cell membrane proteins, and cytoskeleton proteins influence bone tissue cells' morphology, proliferation, and differentiation. The topography, chemistry, and surface energy also determine cell behavior in contact. The micro-textured implants demonstrate improved osseointegration (direct apposition of bone tissue to the implant) instead of smooth implants by in vivo test ^[2]. Therefore, the organization of surface roughness is an important parameter for the contact guidance phenomenon. The micron-roughened surface morphology can increase the surface area of the implant and the contact between the implant and host bone. In addition, it was demonstrated that osteoblast cells can detect and respond to different nano-topographical features in vitro ^[3]. When nanoscale architecture is combined with underlying rough microstructure, significant improvement in both implant fixation strength and matrix mineralization can be observed ^[4].

Among metallic implant materials, titanium and its alloys are considered to be the best choice for bone implant applications because of their low modulus of elasticity, corrosion resistance, and biocompatibility [4]. Unfortunately, Ti6Al4V alloy, which is most widely used, has low wear resistance and the debris generated during wear accelerates electrochemical reactions between the physiological environment and implant surface [5]. Moreover, the alloy loses biocompatibility if V and Al ions are released in human tissue, because Al can cause neurological diseases while V ions are cytotoxic [6]. Therefore, further developments that extend the longevity and bioactivity of these implant materials are needed.

For improving osteoconductivity and osteoinductivity of titanium implants, bioceramic coatings such as nanoclays [7], hydroxyapatite [8], and calcium silicate [9] have been utilized. However, these coatings demonstrate insufficient strength and fracture toughness for load-bearing applications in implantology [10]. TiN coatings applied to orthopedic alloys are well-known materials that positively affect the tribological properties of bone grafts by reducing the coefficient of friction [11], wear [12] and increasing hardness and scratch resistance [13]. Such tribological performance of a coating will help to enhance the service life of articulating implants if at high contact pressure the elastic recovery of the hard coating and soft alloy does not differ substantially. TiN-coated Ti6Al4V alloy also demonstrated biocompatibility [14] and reduction of ion release rate [15] compared to uncoated alloy. Nonetheless, studies of cell proliferation and differentiation on TiN-coated materials are contradictory: several papers report no difference in proliferation compared to controls [16][17], while other studies demonstrate an increase in proliferation [18]. Moreover, concerns were raised about PVD-coated Ti6Al4V with TiN because it suffered from coating failure due to either defects in the film [19] or higher difference in elastic modulus of Ti6Al4V substrate and TiN film [14].

On the one hand: this condition could be improved by applying suitable initial surface modification such as electron beam treatment to increase surface roughness and raise surface hardness values and, hence—elastic modulus of Ti6Al4V alloy before TiN deposition. That will reduce the risk of delamination due to the gradient-like hardness profile of the substrate. A feasible method for producing micro- and sub-micrometer surface texturing on metallic materials is the direct laser interference patterning (DLIP) that directly removes material by ablation [20]. However, when utilizing double-pulse generation 50% of laser energy is lost while treating metal surfaces [21] which makes the depth of the substrate strengthening lower. According to some authors [22], the formation of preferred crystallographic orientation that influences mechanical properties can explain the differences in the hardening mechanism of laser- and electron-beam processed metal surfaces. EBM can be carried out in different geometries of scanning (linear, circular, etc.) because charged electrons can be deflected and precisely guided [23]. This modification leads to direct structuring of the surface by periodical topography in a high vacuum state. Thus, low pressure prevents oxidation of easily oxidized titanium alloys and hinders the formation of brittle surface layer (the so-called alfa case) that affects negatively the mechanical properties and fatigue resistance of the alloy [24].

On the other hand, to increase bone formation and bonding strength, deposition of TiO₂ coating on TiN film's surface is a promising approach that could further improve the corrosion resistance of the coating [25], covering the nitride defects. TiO₂ coatings are well-suited as protective non-toxic hydrophilic coatings in medical applications in which additional benefits like self-cleaning and anti-bacterial effects can be obtained [26]. It was also shown that

anatase and mixtures of anatase-rutile crystallographic forms of TiO_2 exhibited more efficient apatite formation than amorphous structures [27]. Additionally, nanostructured TiO_2 exhibited higher bone growth values and bone-to-implant contact area [28]. Since the biological response is affected by the chemistry and topography of the implant material, the osteoblastic response of the cells to deposited TiO_2 on the surface of TiN film is a highly interesting field of research.

A number of different techniques have been used for producing ceramic TiN and TiO_2 films such as magnetron sputtering [29], high power impulse magnetron sputtering (HIPIMS) [30], CVD [31], ion beam-enhanced deposition [32], electron-beam deposition [33], low pressure plasma spray [34], dual plasma deposition [35], laser deposition [36], plasma ion nitriding [37], plasma immersion ion implantation [38], cathodic arc deposition [39][40][41]. The low process temperature allows the coating material to be deposited without reduction in hardness, corrosion resistance or distortion compared to techniques conducted at higher temperatures [42]. Except for low-temperature deposition, cathodic arc deposition offers an effective source of ionized, energetic material to produce well adherent and dense coatings at high deposition rates [43]. However, this technique has not been fully exploited for the production of biocompatible coatings on Ti6Al4V substrates. In our previous studies, TiN/ TiO_2 coatings were found to improve the hydrophilicity and anti-corrosion properties in Ringer solution of titanium alloy with lower aluminium content (Ti5Al4V) [44][45]. At the same time, we demonstrated that TiN/ TiO_2 coatings deposited on polished Ti6Al4V promoted cell adhesion without inhibiting cell viability [46].

2. Discussion

In Vitro Biocompatibility

The supportive effect of TiN/ TiO_2 coatings on cell adhesion and viability was demonstrated when the polished AR sample was compared to the polished and EBM-coated samples. Compared to the uncoated group, TiN/ TiO_2 -coated samples' cell attachment efficiency was better (**Figure 1A**). It is known that nano- and submicron-structured crystalline particles have higher surface charge densities than bulk materials [47]. Therefore, the small crystalline TiO_2 has a higher negative surface charge that is expected to show a high affinity to some positively/negatively charged cell-adhesion mediated molecules. Considering different extracellular matrix (ECM) proteins, Price et al. stated that due to its relatively linear and small molecule, vitronectin recognized by osteoblasts is preferentially adsorbed to nano-crystalline surfaces [48]. Moreover, cell attachment is affected by the surface roughness of samples. As opposed to AR and AR500 samples, AR850 specimens before and after coating deposition demonstrated higher attachment efficiency. Therefore, the surface's organization in isotropic roughness with a higher distance between the grooves (above 42 μm), lower peak-to-valley (R_z) values and predominate valley areas influence the attachment response of MG63 cells. It follows that cell adhesion can be governed by well-defined roughness features comparative to osteoblast cell size (approximately 20 μm [49]). That fact can be explained by the flexible and elastic external cell membrane that is prone to accommodate small features and/or complex surface topographies [50]. That initial accommodation can be better achieved on a less rough surface such as that on AR850 rather than on AR or AR500 irrespective of the presence/absence of the coating. Moreover, the

change in surface energy related to coating structuring and phase composition was found to be able to modulate protein adsorption which further regulates cell adhesion and spreading [51].

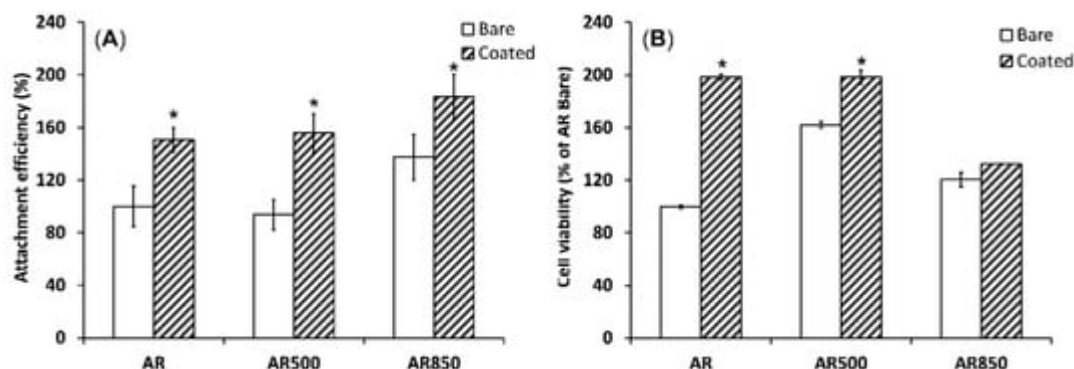


Figure 1. Cell attachment after 1 h (A) and cell viability evaluated by MTT assay (B) of MG63 growing on uncoated and coated samples for 24 h. * $p < 0.01$ compared to the AR sample, $n = 2$.

The deposition of TiN/TiO₂ coating also promoted cell viability during the initial 24 h compared to uncoated Ti5Al4V substrates (Figure 1B). However, cell viability on AR850-coated and the uncoated alloy was found to be lower than that on AR500 samples. It was claimed that micro- and nanometer peaks and valleys on implant surfaces were found to affect the cytoskeleton organization and intracellular transduction signaling pathways [52]. Moreover, the decreased viability on the coated AR850 sample could be associated with the presence of a greater fraction of anatase in the oxide since it was found that dissolution of Ti ions from the rutile phase was one order of magnitude lower than that of anatase [35].

The cell morphology of MG63 osteoblasts on each bare and coated surface was investigated by fluorescent microscopy following a cytoskeleton formation. Representative results are shown in Figure 2. The cells of the mechanically polished surface exhibited a flat phenotype typical for osteoblasts cultured on such surfaces [49], forming a monolayer. The cells attached to the coatings displayed polygonal elongated morphology extending from the main body filopodia and lamellipodia suggesting more differentiated physiology and direct focal contacts with the coating. A certain amount of filopodia was found for cells cultured on bare substrates but not as many as identified on the coated samples' surface. Further, MG63 cell morphology was not abnormal when seeded on TiN/TiO₂ coatings, suggesting that the nanostructured coatings were non-cytotoxic. After 24 h, cells on coated specimens exhibited long extensions of cytoplasmic membranes, making the cells fully spreading out the shape.

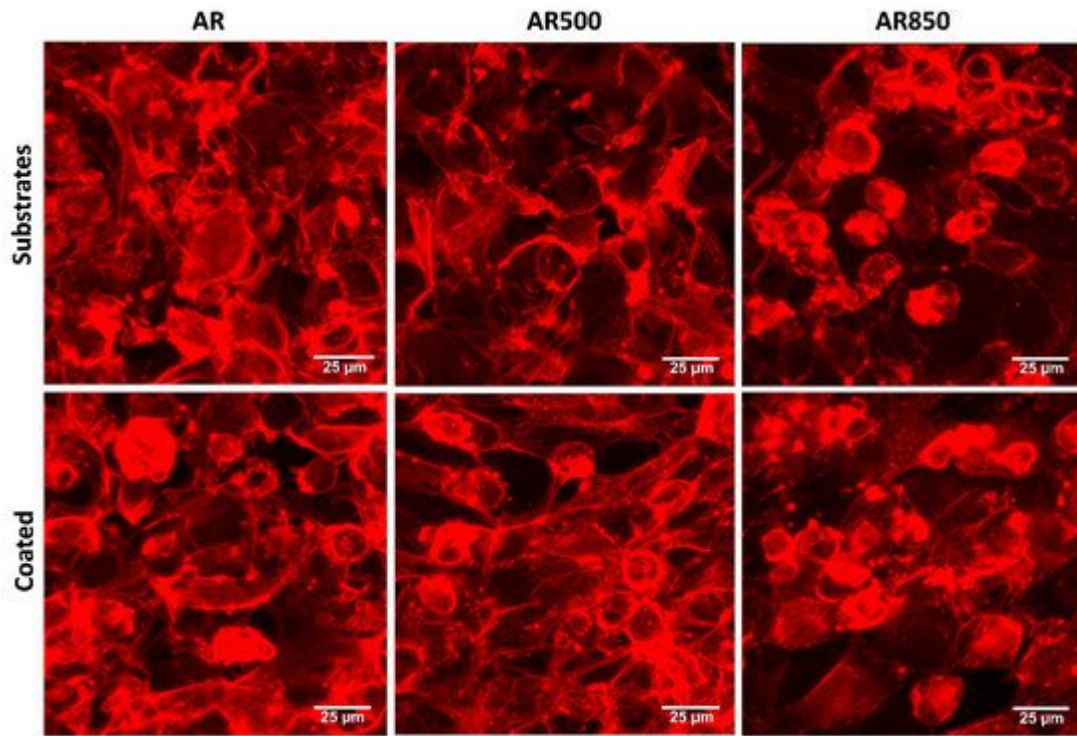


Figure 2. Representative fluorescent images showing cell morphology of MG63 cultured on bare and coated substrates for 24 h. The cytoskeleton was visualized by F-actin staining. Bars 25 μm .

The depth and width of grooves can determine the focal contacts of osteoblasts and the way they mineralize their matrix. For that reason, after 31 days of osteogenic induction, differentiation-induced calcium nodules on the surface of all samples were stained and measured by a quantitative colorimetric assay. The bone mineralization activity was found to be higher on the coated samples than on uncoated ones (**Figure 3**).

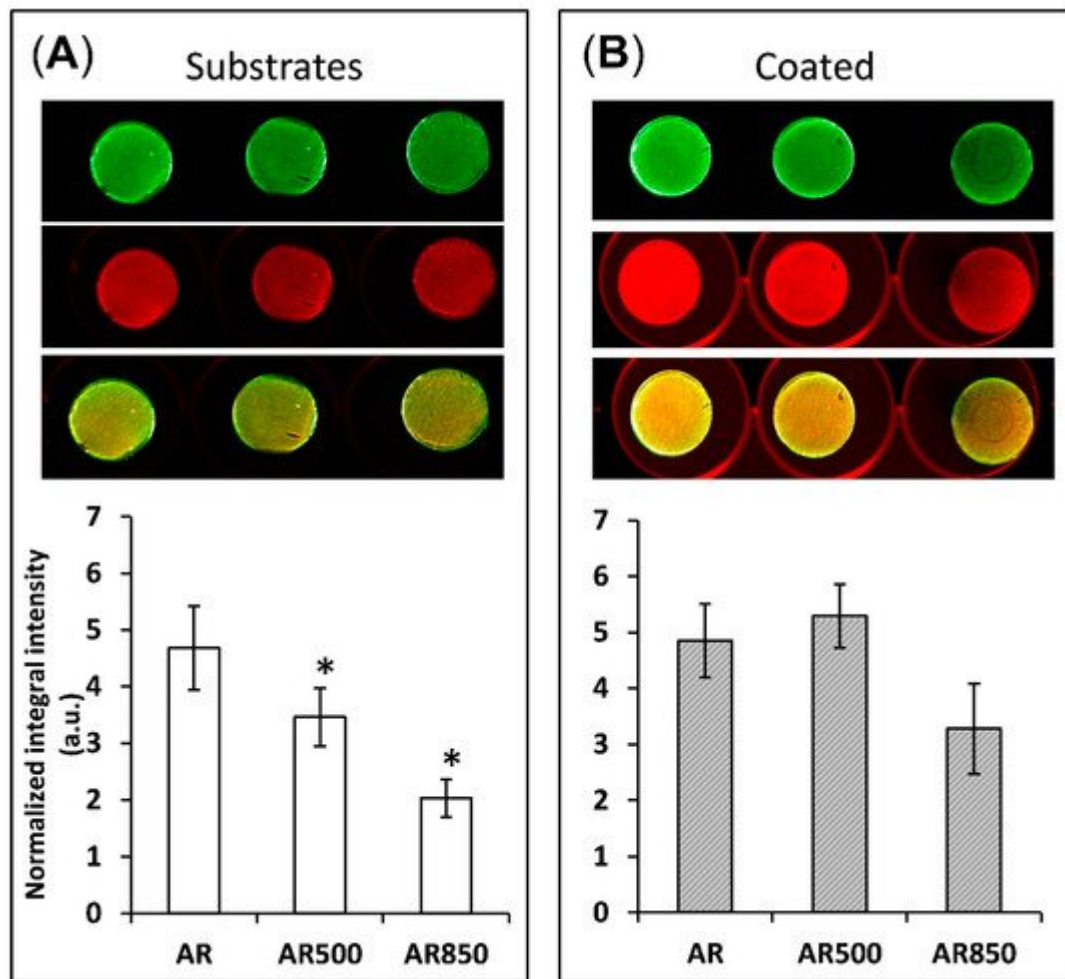


Figure 3. Bone mineralization activity of (A) uncoated and (B) coated samples after 31 days post-seeding of MG63 cells. * $p < 0.01$ compared to the AR sample. Mineralization was visualized by BoneTag CW800 (green) and cells by CellTag700 (red). * $p < 0.05$ compare to AR, $n = 3$.

On the surface of EBM substrates (**Figure 3A**), osteoblasts tend to form congregates of calcium nodules in the cavities following the trajectory of the grooves. Similar behaviour of suppressed cell spreading on microroughened surfaces was also observed by Aita et al. [53]. However, even on the mechanically polished samples, calcium nodules were not homogeneously distributed on the surface (**Figure 3A**). In contrast, all coated samples displayed a more homogenous distribution of nodules on their surfaces. This fact indicates that the cells cultured on coated samples form focal attachments that allow them to spread across structures and build a homogeneously mineralized matrix, especially on the coated AR500 samples. It follows that the coating boosted and enhanced cell differentiation. These favourable results can be explained by the relatively large material surface area available for cell adhesion, proliferation, differentiation and a change in spatial cell arrangement and protein adsorption. The present study indicates that the proposed hybrid treatment has a notable effect on biofilm formation like other surface modifying approaches referred to in [54]. It is generally considered that rapid bone mineral deposition on the surface of the implant results in earlier stabilization of the alloplastic material [55]. However, the changes that osteoblast cells undergo are complex and not easy to explain simply as a function of surface micro- and nanoarchitecture. For that reason, a limitation of our study is that we do not examine the profiles of gene

expression and enzyme activity that control osteoclast differentiation as well as the relative rates of proliferation on each surface. Another limitation is that the influence of different rutile-to-anatase ratios in TiO_2 should be clarified separately by samples with fixed weight percentages of both phases in the coatings. However, because of the naturally occurring processes that were earlier discussed, we consider coatings with changing rutile-to-anatase ratio while taking it into account in the present paper. Solving these two issues will be a task for our future studies.

References

1. Anselme, K. Osteoblast adhesion on biomaterials. *Biomaterials* 2000, 21, 667–681.
2. Zhou, R.; Wei, D.; Cao, J.; Feng, W.; Cheng, S.; Du, Q.; Li, B.; Wang, Y.; Jia, D.; Zhou, Y. Synergistic effect of surface chemistry and topologic structure from modified microarc oxidation coatings on Ti implants for improving osseointegration. *ACS Appl. Mater. Interfaces* 2015, 7, 8932–8941.
3. Zhang, B.G.X.; Myers, D.E.; Wallace, G.G.; Brandt, M.; Choong, P.F.M. Bioactive coatings for orthopaedic implants-recent trends in development of implant coatings. *Int. J. Mol. Sci.* 2014, 15, 11878–11921.
4. Ferraris, S.; Venturello, A.; Miola, M.; Cochis, A.; Rimondini, L.; Spriano, S. Antibacterial and bioactive nanostructured titanium surfaces for bone integration. *Appl. Surf. Sci.* 2014, 311, 279–291.
5. Gilbert, J.L.; Buckley, C.A.; Jacobs, J.J. In vivo corrosion of modular hip prosthesis components in mixed and similar metal combinations. The effect of crevice, stress, motion, and alloy coupling. *J. Biomed. Mater. Res.* 1993, 27, 1533–1544.
6. Runa, M.J.; Mathew, M.T.; Rocha, L.A. Tribocorrosion response of the Ti6Al4V alloys commonly used in femoral stems. *Tribol. Int.* 2013, 68, 85–93.
7. Gaharwar, A.K.; Mihaila, S.M.; Swami, A.; Patel, A.; Sant, S.; Reis, R.L.; Marques, A.P.; Gomes, M.E.; Khademhosseini, A. Bioactive silicate nanoplatelets for osteogenic differentiation of human mesenchymal stem cells. *Adv. Mater.* 2013, 25, 3329–3336.
8. Arifin, A.; Sulong, A.B.; Muhamad, N.; Syarif, J.; Ramli, M.I. Material processing of hydroxyapatite and titanium alloy (HA/Ti) composite as implant materials using powder metallurgy: A review. *Mater. Des.* 2014, 55, 165–175.
9. Mehrali, M.; Akhiani, A.R.; Talebian, S.; Mehrali, M.; Latibari, S.T.; DolatshahiPirouz, A.; Metselaar, H.S.C. Electrophoretic deposition of calcium silicate–reduced graphene oxide composites on titanium substrate. *J. Eur. Ceram. Soc.* 2016, 36, 319–332.
10. Shirazi, F.S.; Mehrali, M.; Oshkour, A.A.; Metselaar, H.S.C.; Kadri, N.A.; Abu Osman, N.A. Mechanical and physical properties of calcium silicate/alumina composite for biomedical

- engineering applications. *J. Mech. Behav. Biomed. Mater.* 2014, 30, 168–175.
11. Hussein, M.A.; Ankah, N.K.; Kumar, A.M.; Azeem, M.A.; Saravanan, S.; Sorour, A.A.; Al Aqeeli, N. Mechanical, biocorrosion, and antibacterial properties of nanocrystalline TiN coating for orthopedic applications. *Ceram. Int.* 2020, 46, 18573–18583.
 12. Datta, S.; Das, M.; Balla, V.K.; Bodhak, S.; Murugesan, V.K. Mechanical, wear, corrosion and biological properties of arc deposited titanium nitride coatings. *Surf. Coat. Technol.* 2018, 344, 214–222.
 13. Galvin, A.; Brockett, C.; Williams, S.; Hatto, P.; Burton, A.; Isaac, G.; Stone, M.; Ingham, E.; Fisher, J. Comparison of wear of ultra-high molecular weight polyethylene acetabular cups against surface-engineered femoral heads. *Proc. Inst. Mech. Eng. Part H J. Eng. Med.* 2008, 222, 1073–1080.
 14. Van Hove, R.P.; Sierevelt, I.N.; Van Royen, B.J.; Nolte, P.A. Titanium-Nitride Coating of Orthopaedic Implants: A Review of the Literature. *Biomed. Res. Int.* 2015, 2015, 485975.
 15. Gordin, D.M.; Gloriant, T.; Chane-Pane, V.; Busardo, D.; Mitran, V.; Höche, D.; Vasilescu, C.; Drob, S.I.; Cimpean, A. Surface characterization and biocompatibility of titanium alloys implanted with nitrogen by Hardion+ technology. *J. Mater. Sci. Mater. Med.* 2012, 23, 2953–2966.
 16. Zeng, C.; Wen, H.; Ettefagh, A.H.; Zhang, B.; Gao, J.; Haghsheenas, A.; Raush, J.R.; Guo, S.M. Laser nitriding of titanium surfaces for biomedical applications. *Surf. Coat. Technol.* 2020, 385, 125397.
 17. Czarnowska, E.; Morgiel, J.; Ossowski, M.; Major, R.; Sowinska, A.; Wierzchon, T. Microstructure and biocompatibility of titanium oxides produced on nitrided surface layer under glow discharge conditions. *J. Nanosci. Nanotechnol.* 2011, 11, 8917–8923.
 18. Van Hove, R.P.; Nolte, P.A.; Semeins, C.M.; Klein-Nulend, J. Differences in proliferation, differentiation, and cytokine production by bone cells seeded on titanium-nitride and cobalt-chromium-molybdenum surfaces. *J. Biomater. Appl.* 2013, 28, 278–287.
 19. Komotori, J.; Lee, B.J.; Dong, H.; Dearnley, P.A. Corrosion response of surface engineered titanium alloys damaged by prior abrasion. *Wear* 2001, 250–251, 1239–1249.
 20. Peter, A.; Lutey, A.H.A.; Faas, S.; Romoli, L.; Onuseit, V.; Graf, T. Direct laser interference patterning of stainless steel by ultrashort pulses for antibacterial surfaces. *Opt. Laser Technol.* 2020, 123, 105954.
 21. Fraggelakis, F.; Mincuzzi, G.; Lopez, J.; Manek-Hönninger, I.; Kling, R. Controlling 2D laser nano structuring over large area with double femtosecond pulses. *Appl. Surf. Sci.* 2019, 470, 677–686.
 22. Abbaschian, R.; Abbaschian, L.; Reed-Hill, R. *Physical Metallurgy Principles*, 4th ed.; CL Engineering: Stamford, CT, USA, 2008.

23. Valkov, S.; Ormanova, M.; Petrov, P. Surface Manufacturing of Materials by High Energy Fluxes. In *Advanced Surface Engineering Research*; Chowdhury, M.A., Ed.; IntechOpen: London, UK, 2018.
24. Gaddam, R.; Sefer, B.; Pederson, R.; Antti, M.-L. Study of alpha-case depth in Ti-6Al-2Sn-4Zr-2Mo and Ti-6Al-4V. *IOP Conf. Ser. Mater. Sci. Eng.* 2013, 48, 012002.
25. Hussein, M.A.; Kumar, A.M.; Ankah, N.; Azeem, M.A. Thermal treatment effect on the surface and in vitro corrosion characteristics of arc deposited TiN coating on Ti alloy for orthopedic applications. *Ceram. Int.* 2021.
26. Markowska-Szczupak, A.; Ulfig, K.; Morawski, A. The Application of Titanium Dioxide for Deactivation of Bioparticulates: An Overview. *Catal. Today* 2011, 169, 249–257.
27. Bai, Y.; Park, I.S.; Park, H.H.; Lee, M.H.; Bae, T.S.; Duncan, W.; Swain, M. The effect of annealing temperatures on surface properties, hydroxyapatite growth and cell behaviors of TiO₂ nanotubes. *Surf. Interface Anal.* 2011, 43, 998–1005.
28. Salou, L.; Hoornaert, A.; Louarn, G.; Layrolle, P. Enhanced osseointegration of titanium implants with nanostructured surfaces: An experimental study in rabbits. *Acta Biomater.* 2015, 11, 494–502.
29. Čolović, B.M.; Kisić, D.; Jokanović, B.; Rakočević, Z.L.; Nasov, I.; Petkoska, A.T.; Jokanović, V.R. Wetting properties of titanium oxides, oxynitrides and nitrides obtained by DC and pulsed magnetron sputtering and cathodic arc evaporation. *Mater. Sci. Poland.* 2019, 37, 173–181.
30. Kuo, C.-C.; Lin, Y.-T.; Chan, A.; Chang, J.-T. High Temperature Wear Behavior of Titanium Nitride Coating Deposited Using High Power Impulse Magnetron Sputtering. *Coatings* 2019, 9, 555.
31. Song, S.H.; Min, B.K.; Hong, M.-H.; Kwon, T.-Y. Application of a Novel CVD TiN Coating on a Biomedical Co–Cr Alloy: An Evaluation of Coating Layer and Substrate Characteristics. *Materials* 2020, 13, 1145.
32. Nan, H.; Ping, Y.; Xuan, C.; Yongxang, L.; Xiaolan, Z.; Guangjun, C.; Zihong, Z.; Feng, Z.; Yuanru, C.; Xianghuai, L.; et al. Blood compatibility of amorphous titanium oxide films synthesized by ion beam enhanced deposition. *Biomaterials* 1998, 19, 771–776.
33. Ramaseshan, R.; Jose, F.; Rajagopalan, S.; Dash, S. Preferentially oriented electron beam deposited TiN thin films using focused jet of nitrogen gas. *Surf. Eng.* 2016, 32, 834–839.
34. Vautherin, B.; Planche, M.P.; Quet, A.; Bianchi, L.; Montavon, G. Manufacturing of composite titanium-titanium nitride coatings by reactive very low pressure plasma spraying (R-VLPPS). *J. Phys. Conf. Ser.* 2014, 550, 12035–12044.
35. Leng, Y.X.; Huang, N.; Yang, P.; Chen, J.Y.; Sun, H.; Wang, J.; Wan, G.J.; Tian, X.B.; Fu, R.K.Y.; Wang, L.P.; et al. Structure and properties of biomedical TiO₂ films synthesized by dual plasma

- deposition. *Surf. Coat. Technol.* 2002, 156, 295–300.
36. Suda, Y.; Kawasaki, H.; Ueda, T.; Ohshima, T. Preparation of high quality nitrogen doped TiO₂ thin films as a photocatalyst using a pulsed laser deposition method. *Thin Solid Films* 2004, 453–454, 162–166.
 37. Maurer, A.M.; Brown, S.A.; Payer, J.H.; Merritt, K.; Kawalec, J.S. Reduction of fretting corrosion of Ti-6Al-4V by various surface treatments. *J. Orthop. Res.* 1993, 11, 865–873.
 38. Yeung, K.W.; Poon, R.W.; Chu, P.K.; Chung, C.Y.; Liu, X.Y.; Lu, W.W.; Chan, D.; Chan, S.C.; Luk, K.D.; Cheung, K.M. Surface mechanical properties, corrosion resistance, and cytocompatibility of nitrogen plasma-implanted nickel-titanium alloys: A comparative study with commonly used medical grade materials. *J. Biomed. Mater. Res. Part A* 2007, 82, 403–414.
 39. Kelly, P.; Li, H.; Benson, P.; Whitehead, K.; Verran, J.; Arnell, R.D.; Iordanova, I. Comparison of the tribological and antimicrobial properties of CrN/Ag, ZrN/Ag, TiN/Ag, and TiN/Cu nanocomposite coatings. *Surf. Coat. Technol.* 2010, 205, 1606–1610.
 40. Bendavid, A.; Martin, P.; Jamting, Å.; Takikawa, H. Structural and optical properties of titanium oxide thin films deposited by filtered arc deposition. *Thin Solid Films* 1999, 355, 6–11.
 41. Hussein, M.A.; Adesina, A.Y.; Kumar, A.M.; Sorour, A.A.; Ankah, N.; Al-Aqeeli, N. Mechanical, in-vitro corrosion, and tribological characteristics of TiN coating produced by cathodic arc physical vapor deposition on Ti₂₀Nb₁₃Zr alloy for biomedical applications. *Thin Solid Films* 2020, 709, 138183.
 42. Mohseni, E.; Zalnezhad, E.; Bushroa, A.R.; Hamouda, A.M.; Goh, B.T.; Yoon, G. Ti/TiN/HA coating on Ti-6Al-4V for biomedical applications. *Ceram. Int.* 2015, 41, 14447–14457.
 43. Vyskočil, J.; Musil, J. Cathodic arc evaporation in thin film technology. *J. Vac. Sci. Technol. A* 1992, 10, 1740–1748.
 44. Nikolova, M.P.; Nikolov, V.; Valkov, S.; Yankov, E.; Zaharieva, V.; Petrov, P. Ethylene Oxide Sterilization of TiN/TiO₂ Coated Titanium Implant Material. *Key Eng. Mater.* 2019, 813, 178–184.
 45. Nikolova, M.P.; Yankov, E.; Hikov, T.; Dechev, D.; Ivanov, N.; Parshorov, S.; Zaharieva, V.; Petrov, P. Comparison of the Corrosion Behaviour of Differently Deposited PVD TiN/TiO₂ Coatings on Electron Beam Modified Ti5Al4V Alloy. *IOP Conf. Ser. Mater. Sci. Eng.* 2018, 416, 012058.
 46. Nikolova, M.P.; Nikolova, V.; Ivanova, V.L.; Valkov, S.; Petrov, P.; Apostolova, M.D. Mechanical Properties and In Vitro Biocompatibility Evaluation of TiN/TiO₂ Coated Ti6Al4V Alloy. *Mater. Today Proc.* 2020, 33, 1781–1786.
 47. Vayssieres, L.; Chaneac, C.; Tronc, E.; Jolivet, J.P. Size Tailoring of Magnetite Particles Formed by Aqueous Precipitation: An Example of Thermodynamic Stability of Nanometric Oxide Particles. *J. Colloid Interf. Sci.* 1998, 205, 205–212.

48. Price, R.L.; Elloson, K.; Haberstroh, K.M.; Webster, T.J. Nanometer surface roughness increases select osteoblast adhesion on carbon nanofiber compacts. *J. Biomed. Mater. Res. A* 2004, 70, 129–138.
49. Zinger, O.; Zhao, G.; Schwartz, Z.; Simpson, J.; Wieland, M.; Landolt, D.; Boyan, B. Differential regulation of osteoblasts by substrate microstructural features. *Biomaterials* 2005, 26, 1837–1847.
50. Pacha-Olivenza, M.Á.; Tejero, R.; Fernández-Calderón, M.C.; Anitua, E.; Troya, M.; González-Martín, M.L. Relevance of Topographic Parameters on the Adhesion and Proliferation of Human Gingival Fibroblasts and Oral Bacterial Strains. *BioMed. Res. Int.* 2019, 2019, 845634.
51. Kennedy, S.B.; Washburn, N.R.; Jr, C.G.S.; Amis, E.J. Combinatorial screen of the effect of surface energy on fibronectin-mediated osteoblast adhesion, spreading and proliferation. *Biomaterials* 2006, 27, 3817–3824.
52. Zhao, G.; Raines, A.L.; Wieland, M.; Schwartz, Z.; Boyan, B.D. Requirement for both micron- and submicron scale structure for synergistic responses of osteoblasts to substrate surface energy and topography. *Biomaterials* 2007, 28, 2821–2829.
53. Aita, H.; Hori, N.; Takeuchi, M.; Suzuki, T.; Yamada, M.; Anpo, M.; Ogawa, T. The effect of ultraviolet functionalization of titanium on integration with bone. *Biomaterials* 2009, 30, 1015–1025.
54. Kligman, S.; Ren, Z.; Chung, C.-H.; Perillo, M.A.; Chang, Y.-C.; Koo, H.; Zheng, Z.; Li, C. The Impact of Dental Implant Surface Modifications on Osseointegration and Biofilm Formation. *J. Clin. Med.* 2021, 10, 1641.
55. Garcia, A.J.; Reyes, C.D. Bio-adhesive surfaces to promote osteoblast differentiation and bone formation. *J. Dent. Res.* 2005, 84, 407–413.

Retrieved from <https://encyclopedia.pub/entry/history/show/28960>