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OXIDE CERAMIC COATINGS ON ORTHOPAEDIC IMPLANTS: A REVIEW OF TIO_2 AND AL_2O_3

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Ceramic coatings like TiO_2 and Al_2O_3 have shown great promise in enhancing the surface properties of metallic orthopaedic implants. This comprehensive review summarises the latest advances in deposition techniques, performance evaluations, and the clinical outcomes of TiO_2 and Al_2O_3 coated implants. Magnetron sputtering enables uniform and adherent TiO_2 and Al_2O_3 coatings, but has limitations in coating complex geometries. Micro-arc oxidation can rapidly produce thick porous oxide layers directly on the implant, but the precise control of coating properties is difficult. Numerous studies demonstrate TiO_2 coatings can significantly improve the corrosion resistance, wear resistance, and antibacterial properties of Ti, Co-Cr, and stainless steel implants. TiO_2 coatings also appear to promote osseointegration in vitro, but TiO_2 evidence is limited. Al_2O_3 coatings reduce metal ion release and polyethylene wear for alloy implants, but long-term clinical data is sparse. While both coatings have benefits, TiO_2 demonstrates better osseointegration potential while Al_2O_3 is more bioinert. Composite coatings are being explored to harness the synergistic effects. Persistent challenges include coating stresses, thickness uniformity, durability concerns, and long-term clinical evidence.

INTRODUCTION

Orthopaedic implants play a crucial role in replacing and restoring the function of damaged or diseased bones and joints. The global market for orthopaedic implants was valued at around $45 billion in 2020 and is projected to grow to over $66 billion by 2027 [1]. The most common materials used for orthopaedic implants include metals, polymers, and ceramics [2]. Metallic implants made of stainless steel, cobalt-chromium alloys, and titanium alloys are the most prevalent due to their high strength and fracture toughness [3]. However, issues like corrosion, wear, and biocompatibility of metal implants have led to the increased use of ceramics and polymers [4]. Ceramics, such as alumina and zirconia, are favoured for their hardness, wear resistance, and biocompatibility, but have limitations like brittleness and fracture [5]. Polymers, such as ultra high molecular weight polyethylene, demonstrate excellent biocompatibility, but have poor mechanical strength [6].

There has been extensive research in the last few decades to improve the performance and longevity of orthopaedic implants. One of the most widely adopted strategies is the application of coatings onto the implant surface [7]. Ceramic coatings have shown particular promise in enhancing the surface properties of implant materials [8]. Ceramic coatings can impart corrosion and wear resistance, biocompatibility, antibacterial effects, and improved osseointegration. The two most extensively studied ceramic coatings for orthopaedic applications are TiO_2 and Al_2O_3 [9]. The high hardness, chemical stability, and photocatalytic properties of TiO_2 make it an attractive coating for implants. Al_2O_3 coatings also demonstrate high hardness and wear resistance along with bioinertness [10]. This review focuses on the recent progress, applications, and challenges of TiO_2 and Al_2O_3 ceramic coatings for orthopaedic implants.

TiO_2 exists in three mineral forms – anatase, rutile, and brookite, of which anatase and rutile are most commonly used for biomedical coatings [11]. TiO_2 coatings can be deposited by a variety of methods including plasma spraying, the sol-gel technique, micro-arc oxidation, sputtering, and electrophoretic deposition among others [12–18]. Nanostructured TiO_2 coatings in particular have become popular in recent years owing to their improved properties [19–21]. TiO_2 coatings have been shown to enhance the corrosion and wear resistance of Ti, Co-Cr, stainless steel, and other alloy implants by several research groups [22–24]. The semiconducting and photocatalytic properties of TiO_2 have also been implicated in its antibacterial effects against organisms involved in implant infections [25–27]. There is some evidence that nanostructured TiO_2 promotes the adhesion and growth of osteoblasts, thereby improving osseointegration [28]. Early clinical studies with TiO_2 coated femoral stems and acetabular cups have shown lower revision rates compared to uncoated implants [29]. Al_2O_3 coatings are bioinert and demonstrate high hardness, wear resistance, and chemical stability. Micro-arc oxidation and plasma spraying methods have been primarily used to coat Al_2O_3 onto Ti and Co-Cr alloys [30, 31]. Al_2O_3 coatings significantly reduce the metal ion release and corrosion of the underlying alloy implants [32]. The wear rate against polyethylene and risk of osteolysis is lowered with Al_2O_3 coated implants [32]. Some studies indicate Al_2O_3 stimulates osteoblast growth, but does not form a direct biochemical bond with bone, where retrieved Al_2O_3 coated femoral stems showed no signs of coating degradation or delamination even after 15 years [33]. However, long-term clinical data on survival rates with Al_2O_3 coated implants is currently limited.

Both TiO_2 and Al_2O_3 ceramic coatings offer specific benefits, but also have certain limitations. For instance, Al_2O_3 coatings may delaminate under high stresses [34]. TiO_2 coatings demonstrate lower adhesion strength compared to Al_2O_3 [35]. The osseointegration capability of TiO_2 is debated, while Al_2O_3 is considered bioinert [36, 37]. Therefore, the choice of coating would depend on the implant application, location, and expected stresses. TiO_2 coatings on titanium femoral stems and Al_2O_3 coatings on CoCr femoral heads may be an ideal combination. Composite coatings with TiO_2 and Al_2O_3 have also been studied [38]. There is a need for more head-to-head clinical studies comparing the long-term effectiveness of TiO_2 versus Al_2O_3 coatings.

There are some persistent challenges facing the adoption of ceramic coatings. Most deposition techniques generate coating stresses that undermine adhesion to the substrate [39]. Post-deposition heat treatments have been attempted, but with limited success. The thickness uniformity and the coverage of complex implant geometries are issues with thermal spraying methods [40, 41]. Another major concern is the coating durability since wear and delamination have been reported [42]. There is sparse data on the clinical survival of coated implants beyond 10-15 years [43]. The combination of mechanical stresses and physiological environment poses problems. Hence, newer coating materials and deposition processes are needed.

This review aims to provide a comprehensive overview of the current state of the art in TiO_2 and Al_2O_3 ceramic coatings for orthopaedic implants. The specific objectives are:

1. To review the coating deposition processes and the effect of the key parameters on the properties of TiO_2 and Al_2O_3 coatings
2. To systematically assess and compare the published data on corrosion protection, wear resistance, antibacterial activity, and osseointegration provided by TiO_2 and Al_2O_3 coatings.
3. To analyse the outcomes of clinical studies conducted using TiO_2 or Al_2O_3 coated orthopaedic implants
4. To identify the limitations of the existing coating technologies and challenges for future research
5. To provide recommendations for the selection, deposition, and application of TiO_2 and Al_2O_3 coatings tailored to specific orthopaedic implant types.

An extensive literature review was conducted to identify studies on TiO_2 and Al_2O_3 ceramic coatings for orthopaedic applications.

DISCUSSION

Methods of TiO_2 and Al_2O_3 coating deposition

Magnetron sputtering is one of the most commonly used techniques for depositing TiO_2 and Al_2O_3 coatings on implants. In this method, a magnetron source is used to generate a plasma from an inert gas like argon. Figure 1 shows schematic diagram of magnetron sputtering (Figure 1). The target material, either TiO_2 or Al_2O_3, is bombarded by plasma ions, ejecting atoms that deposit on the implant surface forming a thin film coating. Magnetron sputtering offers good control over the coating thickness, uniformity, and adhesion. However, it has limitations in coating complex implant geometries. For example, Chodun et al. [44] investigated the nature of energetic plasma species generated using the gas injection magnetron sputtering (GIMS) technique and how they interact with the substrate during TiO_2 coating deposition. The purpose of using magnetron sputtering was to utilise the benefits of magnetron-generated plasma, while also taking advantage of the higher energy and ionisation that GIMS enables through gas injection pulses. The researchers found that the oscillating low pressure conditions in the GIMS plasma result in less collisional energy losses, allowing plasma species to retain a higher kinetic energy compared

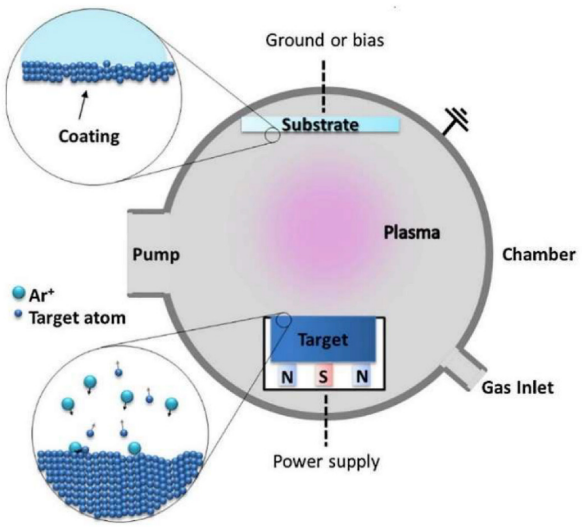

Figure 1. A schematic diagram of magnetron sputtering. Reproduced with permission from [46]. Copyright 2023, Multidisciplinary Digital Publishing Institute (MDPI).

to standard magnetron sputtering at constant higher pressures. Optical emission spectroscopy showed that, with an increasing pressure oscillation amplitude, there were higher populations of ions in the GIMS plasma. When depositing TiO_2 coatings, the GIMS conditions also affected the coating phase composition. Under more stationary plasma conditions, the TiO_2 coating was predominantly the anatase phase, which is a typical result in magnetron sputtering. However, under higher amplitude GIMS oscillations, the metastable rutile phase was favoured, indicating the plasma had more non-equilibrium properties. This demonstrates the higher energy plasma achievable through GIMS. Strong impingement effects of the energetic GIMS plasma species were also observed, as evidenced by the crystallisation of initially amorphous coatings, sputtering of the substrate surface, and formation of a distinct coating-substrate interfacial region. Lin [45] investigated a modified version of high power impulse magnetron sputtering called deep oscillation magnetron sputtering (DOMS) to reactively sputter Al_2O_3 coatings at high deposition rates. Al_2O_3 coatings have applications, such as wear-resistant coatings, due to their high hardness. However, the conventional reactive sputtering of Al_2O_3 suffers from two challenges: 1) low deposition rates due to target poisoning, where the aluminium target surface becomes oxidised, and 2) arcing events that can degrade the coating quality. DOMS aims to overcome these issues by generating high power oscillating voltage pulses on the magnetron target. The authors studied how different DOMS pulse parameters affected arcing events during Al_2O_3 sputtering. They found that using short oscillation pulse on-times (< 4 μs) and longer off-times (> 40 μs) at high currents (130 A) resulted in virtually no arcing. Additionally, they investigated the hysteresis behaviour of the reactive sputtering process under these conditions. The hysteresis behaviour is related to the transition between metallic and fully poisoned modes of the target. To control the reactive sputtering process, the authors utilised the closed-loop feedback control of the oxygen partial pressure by using a plasma emission monitoring sensor. This allowed them to achieve stoichiometric Al_2O_3 coatings with high density and hardness, with deposition rates up to 56 % of the metallic aluminium rate. Overall, the DOMS technique combined with closed-loop control enabled the high-rate deposition of high-quality Al_2O_3 coatings by overcoming the issues of arcing and target poisoning in conventional reactive magnetron sputtering. The key advantage of DOMS is the ability to generate high density plasmas and ionisation of the sputtered material, which improves the coating properties.

Micro-arc oxidation (MAO) is an electrochemical anodization process used to form oxide coatings. The implant forms the anode in an electrolyte containing the desired oxide precursors. An alternating voltage is applied to generate localised micro-arcs on the surface that oxidise and roughen the metal. As the micro-arcs move across the surface, a porous, thick oxide coating is formed (Figure 2). MAO can produce coatings up to 200 μm thick in a single step. However, the coating morphology and composition are difficult to precisely control. For example, Liu et al. [47] investigated the formation mechanism and adhesive strength of a hydroxyapatite (HA)/TiO_2 composite coating deposited on a titanium surface using MAO. The purpose of using MAO was to form a TiO_2 layer initially on the titanium surface, onto which a HA layer could then be coated. This would improve the adhesive strength between the HA and the titanium compared to directly coating HA on titanium. The results showed that in the early stages of MAO treatment, flocculent calcium phosphate (Ca-P) precipitates formed on the porous TiO_2 layer. As the treatment time increased, the Ca-P precipitates transitioned from a flocculent morphology to plate-like shapes that spread across the surface. The Ca-P then

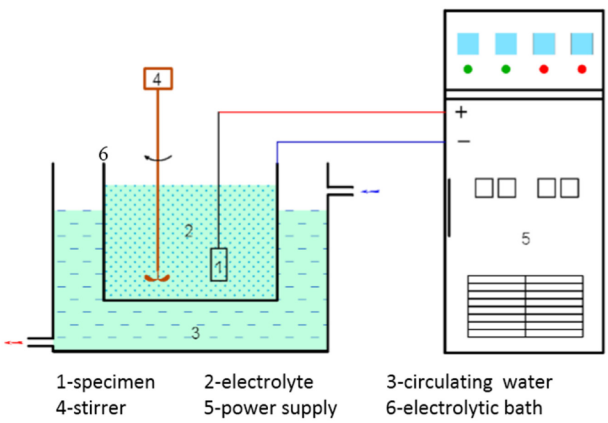

Figure 2. A schematic diagram of MAO. Reproduced with permission from [49]. Copyright 2023, MDPI.

self-assembled into flower-like clusters, completely covering the TiO_2 layer after 3 minutes of treatment. An analysis of the Ca/P ratio at different locations showed it decreased along the coating depth, indicating the Ca^{2+} ion concentration reduced faster than the phosphate ions. The formation mechanism involves the electrolytic breakdown of calcium acetate and monosodium phosphate in the electrolyte to produce Ca^{2+}, PO_4^{3-}, and HPO_4^{2-} ions. The Ca^{2+} ions diffuse into the TiO_2 layer and react with phosphate ions, precipitating as Ca-P. The adhesive strength between the HA and TiO_2 was higher than typically seen between HA and titanium. This is attributed to the interlocking effect between the HA and TiO_2 layers formed simultaneously in the early stages of the one-step MAO process. Li et al. [48] investigated using MAO to produce ceramic coatings on low carbon 10B21 steel containing boron in order to improve its corrosion resistance. Three different electrolyte compositions labelled M1, M2 and M3 were tested, with increasing amounts of Na_2CO_3 and $Na_2B_4O_7$ added to a base of $NaAlO_2$ and NaH_2PO_4. M1 contained only the base electrolytes, M2 added 3 $g \cdot L^{-1}$ of Na_2CO_3, and M3 added 3 $g \cdot L^{-1}$ each of Na_2CO_3 and $Na_2B_4O_7$. The coatings were produced using a voltage of 550V at a frequency of 1200Hz for 30 minutes at 40 °C. the X-ray diffraction (XRD) analysis showed the M1 coating was composed of Al_2O_3, $FePO_4$ and some Fe_2O_3. M2 and M3 contained higher percentages of the α-Al_2O_3 phase rather than γ-Al_2O_3, indicating the additives promoted α-Al_2O_3 growth. The scanning electron microscopy (SEM) imaging revealed M3 had the most uniform coating thickness of 100 ± 10μm without gaps between coating and substrate. The electrochemical testing demonstrated M3, with the most additives, had the best corrosion performance. Its corrosion current density was 2.7 $\mu A \cdot cm^{-2}$ compared to 22 $\mu A \cdot cm^{-2}$ for the untreated steel. After neutral salt spray testing for 7 days, M3 had a corrosion rate of 53 $g \cdot m^{-2} \cdot h^{-1}$ compared to 860 $g \cdot m^{-2} \cdot h^{-1}$ for the untreated steel.

The sol-gel coating involves immersing the implant in a liquid solution (sol) containing precursors of the oxide material. The precursors undergo hydrolysis and condensation reactions to form a gel coating on the implant surface. The gel is then heat treated to obtain the final oxide coating. Sol-gel coatings can achieve uniform coverage of complex implant shapes. However, cracking of the coating during heat treatment and difficulty in controlling the coating thickness are some of the limitations. For TiO_2 sol-gel coatings, the process typically starts with a titanium alkoxide precursor such as titanium isopropoxide or titanium butoxide. The alkoxide is hydrolysed by the addition of water and an acid or base catalyst. Hydrolysis replaces alkoxide groups with hydroxyl groups. Further condensation reactions between the hydroxyl groups and the remaining alkoxides produce TiO_2 monomers and polymers. The viscosity gradually increases to form a gel that can be coated on substrates by techniques like dip-coating, spin coating or spraying [50]. Heat treatment converts the gel to crystalline TiO_2 coatings. Researchers have utilised TiO_2 sol-gel coatings for diverse applications including self-cleaning glass [51], anti-reflection films [52], and photocatalysis [53]. Alumina sol-gel coatings are similarly prepared from aluminium alkoxide precursors like aluminium sec-butoxide. Acid hydrolysis and condensation result in alumina sols that can coat substrates like metals, polymers and fibres. Yetim et al. [54] synthesised γ-Al_2O_3 coatings on titanium alloys to improve the corrosion resistance. Incorporating graphene in alumina sol-gel has been found to enhance the mechanical and tribological properties of the composite coating [55]. Alumina-zirconia mixed oxide coatings have also been prepared via the co-hydrolysis of the respective alkoxides [56]. The properties of alumina sol-gel coatings make them useful for applications including corrosion protection, wear/scratch resistance, thermal insulation, and more [57].

Other techniques used include physical vapour deposition (PVD), chemical vapour deposition (CVD), and electrodeposition. Each method has its own advantages and limitations related to factors like control over the coating properties, uniformity, ability to coat complex shapes, cost, and environmental impact. An ideal coating technique for implants would offer the precise control over the coating thickness, composition and properties, while achieving uniform coverage of complex implant geometries in a scalable and cost-effective manner. Magnetron sputtering, MAO, the sol-gel method, and other techniques each have their own advantages and limitations for depositing TiO_2 and Al_2O_3 coatings on implants. A comparison can be seen in Table 1. In conclusion, no single coating technique is ideal for all applications. A holistic consideration of the implant material and geometry, required coating properties, feasibility for commercial production, cost, and environmental impact is needed to select the optimal technique. Furthermore, advances that overcome the current limitations could enable the development of next-generation coating processes for orthopaedic implants.

Effects of coatings on the implant performance

Corrosion resistance

TiO_2 and Al_2O_3 coatings have been shown to improve the corrosion resistance of metallic orthopaedic implants like stainless steel, titanium alloys and cobalt alloys. The coatings act as a physical barrier that separates the implant metal from the corrosive body environment. They also make the surface more chemically inert and resistant to corrosion.

Several studies have demonstrated the enhanced corrosion resistance of TiO_2 coated implants. Lorenzetti et al. [58] investigated the use of nanostructured anatase

Table 1. Advantages and limitations of magnetron sputtering, MAO and the sol-gel method for depositing TiO_2 and Al_2O_3 coatings on implants.

Method	Advantages	Limitations
Magnetron sputtering	Precise control over the coating thickness, uniformity and adhesion	Difficulty in uniformly coating complex implant geometries
	Reproducible coating properties	High capital and operating costs
	Compatible with most implant materials	Possible damage to heat sensitive implant materials
MAO	Ability to form thick coatings in a single step	Poor control over coating composition and properties
	Simple and scalable process	Non-uniform coating on complex implant shapes
Sol-gel	Compatible with most implant materials	Possible micro-cracks in the coating
	Uniform coating of complex implant geometries	Cracking of coating during heat treatment
	Easy control over the coating thickness	Difficulty in controlling the coating composition
	Compatible with heat sensitive implant materials	Long coating times

TiO_2 coatings grown via hydrothermal synthesis to enhance the corrosion resistance of titanium-based implants. The anatase coatings were deposited on commercially pure titanium (CP Ti) and a $Ti_{13}Nb_{13}Zr$ alloy, which are commonly used as implant materials. The scanning electron microscopy analysis showed the TiO_2 coatings fully covered the implant surfaces with tightly packed nanocrystals ranging from 10-70 nm in size. The electrochemical corrosion testing revealed that the anatase coatings provided significant improvements to corrosion resistance compared to the bare implant materials (Table 2). Specifically, the corrosion potential was increased by around 200 mV for both the CP Ti and $Ti_{13}Nb_{13}Zr$ alloy after anatase coating, indicating a higher resistance to corrosion. The anatase-coated CP Ti also exhibited a 10-fold decrease in the corrosion current density, related to a lower corrosion rate. The enhanced corrosion protection from the nanostructured anatase coatings is attributed to the dense crystal coverage which acts as a barrier layer, as well as the stability of the anatase phase in physiological conditions. Similarly, Saeed et al. [59] reported that the NiTi alloy samples were fabricated from nickel and titanium powders using powder metallurgy techniques. The samples were compacted, sintered, polished and etched to prepare them for coating. Two types of coatings were applied - TiO_2 coating and a composite hydroxyapatite (HA)/TiO_2 coating. The MAO process was carried out at 280 V for 30 minutes to form a porous, rough oxide layer on the surface. For the composite coating, HA powder was added to the electrolyte. The TiO_2 coating provided a typical porous, rough structure as observed under SEM. The addition of HA led to a flower-like morphology due to HA precipitation and self-assembly during the long MAO process. XRD confirmed the presence of anatase TiO_2 peaks in the single coating and additional HA peaks in the composite coating. The potentiodynamic polarisation tests in Ringer's solution showed that both coatings provided enhanced corrosion resistance compared to uncoated NiTi. The HA/TiO_2 composite coating showed the highest corrosion resistance due to the precipitated HA closing the pores in the TiO_2 layer.

Al_2O_3 coatings have also been shown to enhance the corrosion resistance of implants. A double-layered Al_2O_3 coating was designed with a dense inner layer to enhance the corrosion resistance and prevent aluminium ion leakage, and a porous outer layer to facilitate bone in-growth [32]. Moreover, doping the coating with Ca, Fe,

Table 2. Summary of the synthesis conditions and information about the titania grown crystals for the samples [58].

Sample	Substrate	Ti Ions Source	Additives	HT Time	Estimated Crystal Size after HT
Ti-A	CP Ti	$Ti(iOPr)_4$	–	24 h	30–70 nm
Ti-B	CP Ti	µm-TiO_2	AC, NaOH, TMAH	24 h	10–20 nm
TNZ-C	TNZ	$Ti(iOPr)_4$	AC, NaOH, TMAH	24 h	50–150 nm
TNZ-D	TNZ	$Ti(iOPr)_4$	AC, NaOH, TMAH	12 h	10–20 nm

and Zn was hypothesised to provide additional biological benefits. The MAO process successfully produced uniform Al_2O_3 coatings approximately 5-7 μm thick on the aluminium alloy substrates. The coatings displayed a distinctive two-layer structure, with a compact lower layer adhered to the alloy and a highly porous upper layer. Scratch tests showed the coatings had excellent adhesion strengths over 60 N. The polarisation tests revealed the Al_2O_3 coatings provided exceptional corrosion protection, reducing the corrosion current density by two orders of magnitude compared to the untreated alloy. Immersion in a simulated body fluid confirmed the coatings prevented hazardous aluminium ion release over extended periods. Furthermore, doping the Al_2O_3 coating with Zn imparted remarkable improvements in both the osteogenic activity and antibacterial properties, with near 100 % inhibition of *E. coli* and *S. aureus* bacteria. Similarly, Yu et al. [60] investigated using electrospinning to fabricate Al_2O_3 coatings on zinc as an anti-corrosion barrier for alkaline solutions. Al_2O_3 was chosen because it has excellent corrosion resistance and stability in alkaline environments. The coatings were made by electrospinning a solution containing aluminium nitrate, polyacrylonitrile (PAN), and dimethylformamide (DMF) onto zinc substrates (Figure 3). After electrospinning, the coatings were heat treated to remove solvents and convert the aluminium nitrate to Al_2O_3. The SEM analysis showed the resulting nanofibre coatings were uniform with an average diameter around 220 nm. The anti-corrosion performance of the Al_2O_3 coatings on zinc in a 4 M KOH alkaline solution was evaluated through hydrogen evolution tests, potentiodynamic polarisation, and electrochemical impedance spectroscopy (EIS). It was found that the Al_2O_3 coatings dramatically reduced the corrosion rate and hydrogen evolution of the zinc, with an inhibition efficiency up to 88.5 %. This was attributed to the Al_2O_3 coating preventing the direct contact between the zinc and alkaline solution. Furthermore, increasing the coating thickness improved the anti-corrosion performance, with the 18 μm coating reducing the corrosion current density of zinc from 526 $\mu A \cdot cm^{-2}$ to 60 $\mu A \cdot cm^{-2}$. The thicker coating had higher corrosion resistance and lower porosity.

The corrosion resistance of metallic implants, such as those made of titanium or its alloys, can be significantly enhanced through the application of ceramic coatings like TiO_2 and Al_2O_3. There are several mechanisms by which these oxide coatings provide corrosion protection. Firstly, the ceramic coating acts as a physical barrier that separates and isolates the reactive metal surface from body fluids and electrolytes that can initiate corrosion reactions. By presenting an inert ceramic oxide surface rather than the metallic substrate, the coating prevents direct contact between the metal and corrosive substances in the body environment. Secondly, both TiO_2 and Al_2O_3 are inherently stable and unreactive oxides. Their chemical inertia confers resistance to chemical degradation and dissolution, making the coated surface more passive and corrosion-resistant compared to bare titanium or other alloys. The stable oxide surface does not readily participate in electrochemical reactions that constitute corrosion processes. Thirdly, the ceramic coatings help seal any micro-cracks, pores or defects that may be present on the implant surface. These imperfections can act as pathways for fluids to reach the metal substrate and initiate localised corrosion. The conformal oxide coating blocks these corrosion hotspots. TiO_2 and Al_2O_3 films can also be deposited with a controlled thickness to fully cover surface irregularities and defects. Fourthly, the oxide coatings reinforce and strengthen the natural passive oxide film that spontaneously forms on titanium alloy surfaces. This native surface oxide provides innate

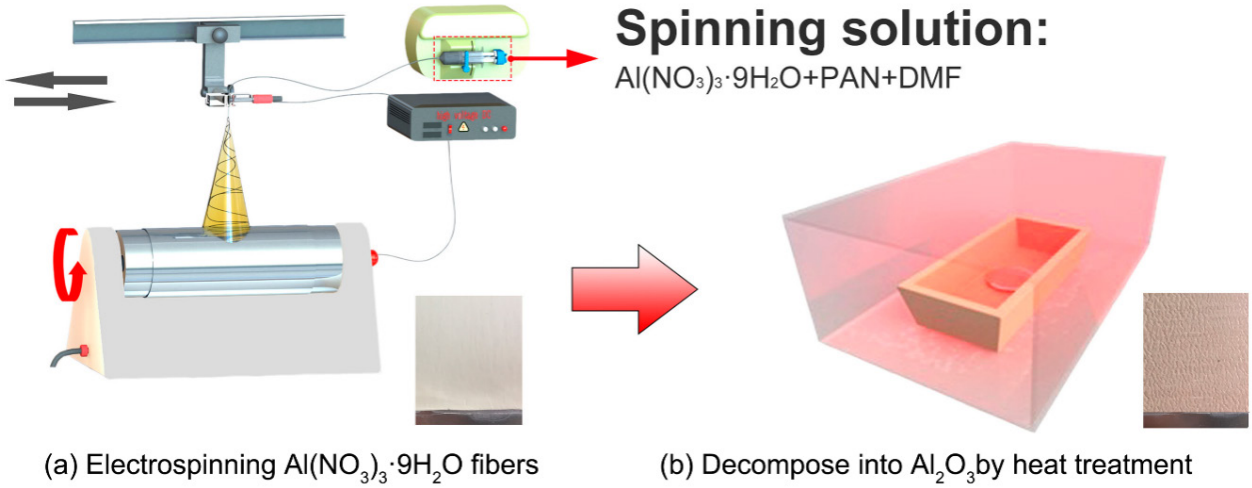

Figure 3. (a) Electrospun $Al(NO_3)_3 \cdot 9H_2O$, PAN and DMF mixed solution on a zinc substrate. (b) Heat treated electrospun films in a muffle furnace in an atmospheric environment to obtain Al_2O_3 coatings [60]. Copyright 2023, MDPI.

corrosion resistance. The ceramic coating augments this natural barrier by increasing the overall thickness and protectiveness of the oxide layer. Finally, the coating hinders ingress of aggressive chloride ions from bodily fluids that can destabilise and breakdown the passive film on titanium surfaces. Chlorides promote localised pitting and crevice corrosion. The ceramic coating acts as a diffusion barrier to limit chlorides from reaching the underlying metal and compromising its passivity.

Wear resistance

Wear is a major cause of implant failure and revision surgery. TiO_2 and Al_2O_3 coatings have been shown to improve the wear resistance of orthopaedic implants, reducing wear debris and prolonging the lifespan of implants.

TiO_2 coatings deposited by various techniques have demonstrated enhanced wear resistance. Wu et al. [61] developed a TiO_2 nanoceramic coating on titanium implant surfaces that can remarkably improve the nanohardness, elastic modulus, and wear resistance compared to pure titanium. Scratch tests showed the coating maintained integrity under progressive loads up to 60 N without delamination. The enhanced mechanical properties were due to the dense nanocrystalline microstructure and strong metallurgical bonding with the titanium substrate achieved through plasma electrolytic oxidation and annealing. Furthermore, in vitro cell culture assays demonstrated that the coating had comparable cytocompatibility and osteoconductivity to pure titanium. Similarly, Çomaklı et al. [62] aimed to improve the wear properties of CP-Ti by depositing TiO_2 coatings using a sol-gel dip coating method. TiO_2 films were coated on CP-Ti substrates and calcined at temperatures ranging from 500 °C to 900 °C. The XRD analysis showed that anatase TiO_2 formed at lower calcination temperatures while rutile TiO_2 was present at temperatures above 700 °C. As the calcination temperature increased, the TiO_2 coating became denser and the thickness increased from 1.2 μm to 2.1 μm. The nanoindentation tests revealed that the hardness and elastic modulus of the TiO_2 coated samples were significantly higher than uncoated CP-Ti. For example, the hardness increased from 2.5 GPa for the uncoated CP-Ti to over 10 GPa for the sample calcined at 900 °C. The increase in mechanical properties is attributed to the formation of the dense rutile phase at higher temperatures. The pin-on-disk wear tests demonstrated that the TiO_2 coatings led to lower friction coefficients, ranging from 0.25 to 0.4 compared to 0.7 for the uncoated CP-Ti. Additionally, the wear rates of the coated samples were nearly an order of magnitude lower than the uncoated sample. The sample calcined at 900 °C exhibited the best wear resistance, with a wear rate of 1.3×10^{-4} $mm^3 \cdot Nm^{-1}$ compared to 1.1×10^{-3} $mm^3 \cdot Nm^{-1}$ for the uncoated CP-Ti. The significant improvement in the wear properties is ascribed to the rutile TiO_2 structure providing a self-lubricating effect at 900 °C.

Al_2O_3 coatings have also been shown to improve the wear resistance of implants. Çomaklı et al. [63] investigated the effect of Ti doping on the wear and corrosion resistance properties of Al_2O_3 ceramic coatings deposited on commercial CP-Ti. The Al_2O_3 and Ti-doped Al_2O_3 coatings were fabricated using a sol-gel dip coating method at various Al_2O_3 to Ti molar ratios. The XRD analysis showed the presence of Al_2O_3 and TiO_2 phases in the coatings, with increasing TiO_2 peaks as the Ti content increased. The SEM revealed the thickness of the coatings increased from 1.2 to 2.4 μm with the higher Ti doping. The wear testing using a pin-on-disk tribometer demonstrated significantly reduced the wear in the ceramic coated samples compared to the uncoated CP-Ti. The Al_2O_3 coating decreased the wear rate by nearly 90 % while the addition of Ti further improved the wear resistance. The lowest wear rate was achieved with a 1:1 Al_2O_3 to Ti ratio, exhibiting a 95 % reduction compared to the uncoated titanium. The increased hardness and thickness of the coatings with Ti doping are believed to enhance the wear performance. The potentiodynamic polarisation and electrochemical impedance spectroscopy tests showed the ceramic coatings provided excellent corrosion protection, with increasing protection as the Ti was incorporated. The Ti-doped Al_2O_3 coatings displayed higher corrosion resistance compared to the undoped Al_2O_3. The results indicate that sol-gel derived Al_2O_3 ceramic coatings can substantially improve the tribological performance of CP-Ti implant materials. The titanium doping of the Al_2O_3 coatings allows further enhancements in wear and corrosion resistance due to the increased hardness, thickness and densification. In another study [64], Al_2O_3 nanoparticles have been used to enhance the wear resistance and load-bearing capacity of an ultra-high molecular weight polyethylene (UHMWPE) nanocomposite coating. The nanocomposite coatings were prepared by incorporating different weight percentages (0.5, 3, 5 and 10 wt. %) of Al_2O_3 nanoparticles into the UHMWPE polymer matrix using a combination of sonication and magnetic stirring to ensure uniform dispersion. The coatings were deposited onto stainless steel substrates using electrostatic spraying followed by post-heat treatment to consolidate the polymer particles. The results showed that up to 5 wt. % Al_2O_3 loading, the nanoparticles were uniformly dispersed in the UHMWPE matrix. However, at 10 wt. % loading, significant agglomeration of the Al_2O_3 particles was observed. The thickness of the coatings increased progressively from around 60 μm for the pure UHMWPE to around 90 μm for the coating with 10 wt. % Al_2O_3. The hardness of the coatings also improved markedly from 0.05 GPa for the unfilled UHMWPE to 0.14 GPa for the coating with the 10 wt. % Al_2O_3 due to the reinforcing effect of the hard ceramic nanoparticles. The tribological testing using a ball-on-disk configuration demonstrated

a dramatic improvement in the wear resistance for the alumina-reinforced UHMWPE coatings compared to the pure UHMWPE. Specifically, the coatings with 3 and 5 wt. % Al_2O_3 reinforcement did not show any signs of failure even after 250,000 cycles under a normal load of 12 N and a sliding speed of 0.1 m·s^{-1} (Figure 4). This was attributed to the solid lubricating effect of the Al_2O_3 nanoparticles along with their ability to carry load.

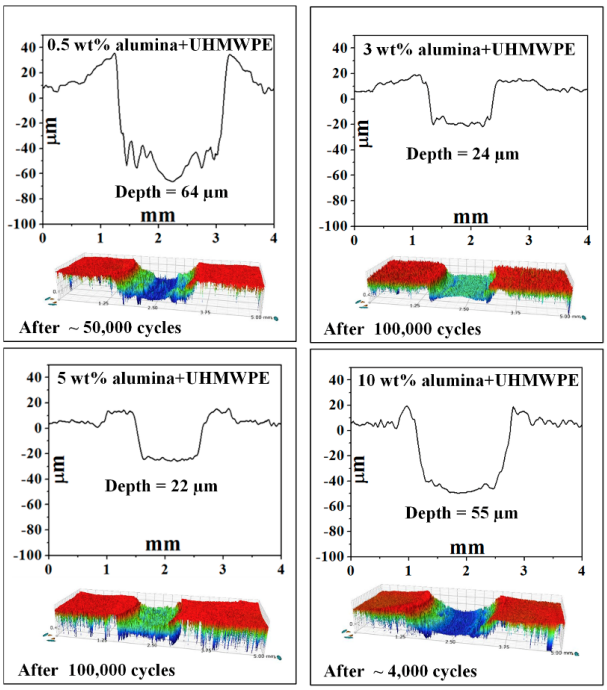

Figure 4. 2D and 3D optical profiles of the wear track for all the nanocomposite coatings after a sliding wear test at a normal load of 12 N and at a sliding speed of 0.1 m·s-1 [60]. Copyright 2023, MDPI.

The mechanisms by which TiO_2 and Al_2O_3 coatings improve the wear resistance of orthopaedic implants are multifaceted. By forming a hard, smooth, and uniform surface layer, TiO_2 and Al_2O_3 coatings enhance the implant's ability to withstand abrasive wear and friction against bone. Specifically, these ceramic coatings seal micro-cracks and pores that may be present in the underlying implant material. This results in a more defect-free coating surface that can better resist the wear and friction forces. Additionally, the hard ceramic coating increases the overall load-bearing capacity of the implant surface while reducing stress concentrations that may arise at surface asperities or roughness peaks. The superior adhesion of the TiO_2 and Al_2O_3 coatings to the implant substrate also prevents delamination and spallation of the coating under applied wear loads. These coatings are very resistant to wear themselves, so they minimise the generation of wear debris particles from the implant that can cause third-body wear. By improving multiple wear mechanisms simultaneously, TiO_2 and Al_2O_3 coatings are able to significantly enhance the overall wear performance and longevity of orthopaedic implants. Clinical results have demonstrated reduced wear rates and particle generation for ceramic-coated implants compared to uncoated devices.

Osseointegration, biocompatibility and antibacterial effects

Osseointegration, the direct structural and functional connection between the implant and bone, is critical for the success of implants. TiO_2 coatings have been shown to promote osseointegration and exhibit good biocompatibility. Miyauchi et al. [65] investigated the effects of UV photofunctionalisation of nanoscale TiO_2 layers on the osteoblast adhesion strength. The authors sputter coated glass plates with a 200 nm TiO_2 layer to create a very smooth surface without roughness or topographical features. One group of plates was then treated with UV light. Rat bone marrow osteoblasts were cultured on the TiO_2 coated plates, with and without the UV treatment. A single cell detachment assay was used to quantify the shear force and energy required to detach individual osteoblasts from the material surfaces after 3 hours and 24 hours. The results showed that the osteoblast adhesion strength was substantially enhanced on the UV treated TiO_2 surfaces compared to the untreated surfaces. After 3 hours, the critical shear force to detach osteoblasts was 2.5 times greater on the UV treated surfaces (1280 nN) versus the untreated surfaces (510 nN). The total energy required for detachment was also 3.5 times higher on the UV treated surfaces (37.0 pJ) compared to the untreated ones (10.5 pJ). Similar enhancements were seen after 24 hours of culture. A further analysis found that the osteoblasts on the UV treated surfaces were larger in size and showed an increased expression of vinculin and the formation of focal adhesions. The density of focal adhesions was not affected, but the total expression and density of the actin fibres increased with the UV treatment. This indicates that the UV photofunctionalisation enhanced the osteoblast adhesion strength by disproportionately increasing focal adhesions and cytoskeletal development. To explore the potential broader applications of this surface modification, the authors also coated cobalt-chromium alloy and polytetrafluoroethylene with a TiO_2 layer and treated it with UV light. This combination synergistically increased the osteoblastic production of alkaline phosphatase compared to the uncoated and untreated surfaces. Overall, the results provide strong evidence that UV photofunctionalisation of nano-thin TiO_2 layers substantially enhances the adhesive strength of the individual osteoblasts. This even occurred on very smooth, topographically featureless surfaces. The findings suggest TiO_2-mediated photofunctionalisation could be a promising technique to improve the

bioactivity of various implant and tissue engineering materials beyond titanium. Bhardwaj and Webster [66] investigated the ability of nanotextured titanium alloy surfaces to reduce bacterial growth while promoting osteoblast proliferation. The surfaces were treated using electrophoretic deposition to create two distinct nanoscale topographies - Ti-160 and Ti-120. Ti-160 was designed to maximise the bacterial growth reduction, while Ti-120 aimed to reduce the bacteria while also increasing the osteoblast activity. The results showed that Ti-160-treated surfaces reduced Staphylococcus aureus by 95.6 %, Pseudomonas aeruginosa by 90.2 %, and ampicillin-resistant Escherichia coli by 81.1 % compared to the untreated titanium alloy. Meanwhile, Ti-120-treated surfaces, while slightly less effective at reducing the bacteria, but substantially increased the osteoblast proliferation. Specifically, Ti-120 surfaces showed 86.8 % less S. aureus, 82.1 % less P. aeruginosa, and 48.6 % less ampicillin-resistant E. coli versus the controls. Importantly, Ti-120 increased the osteoblast proliferation by 120.7 % at 3 days and 168.7 % at 5 days compared to untreated titanium alloy. The increased osteoblast proliferation with the Ti-120 surfaces is a major finding of this study. The ability to not only reduce bacteria, but simultaneously improve the proliferation of osteoblasts is highly desirable for orthopaedic implant applications. An increased osteoblast activity can lead to improved osseointegration between the implant and the bone. The results suggest the nanotexturing approach, especially with a focus on the Ti-120 surface treatment optimised for osteoblast response, could reduce infection while improving the performance of orthopaedic implants.

Biocompatibility studies have shown that TiO_2 and Al_2O_3 coatings exhibit good compatibility with osteoblasts and other cells. For example, Ahmadi and Afshar [67] investigated the development of HA coatings reinforced with TiO_2 and Al_2O_3 nanoparticles on 316L stainless steel substrates using a sol-gel dip coating method. The researchers synthesised HA, TiO_2 and Al_2O_3 sols and combined them in different ratios to create composite coatings containing 20 %, 30 %, and 40 % by weight of TiO_2 + Al_2O_3 nanoparticles. Immersion in a simulated body fluid revealed the reinforced coatings induced the rapid formation of a bone-like apatite layer, indicating good bioactivity. Finally, the cell culture assays showed excellent viability of human osteoblast-like cells on the composite coatings after 24-72 hours, confirming their biocompatibility. The 30 % TiO_2 + Al_2O_3 reinforced HA coating offered the best combination of strong adhesion, corrosion protection, bioactivity, and biocompatibility. In another study, Kang et al. [68] developed volcano-shaped microporous TiO_2 coatings doped with zinc (Zn-MAO) on titanium implants using MAO to improve the implants' bioactivity and antibacterial properties. Different concentrations of zinc acetate were incorporated into the MAO electrolyte solution to control the level of Zn doping in the TiO_2 coatings. An analysis showed the successful incorporation of Zn in the form of Zn^{2+} into the porous TiO_2 coating. In vitro cell culture experiments revealed the Zn-MAO coatings promoted adhesion and proliferation of bone mesenchymal stem cells compared to the pure TiO_2, indicating good biocompatibility (Figure 5). The porous morphology and Zn doping enhanced the bioactivity of the TiO_2 coating. The antibacterial testing showed the Zn-MAO coatings exhibited excellent inhibition against Staphylococcus aureus and Porphyromonas gingivalis, common causative pathogens of implant infections. The antibacterial activity increased with a larger Zn content in the coating. The Zn^{2+} ions released from the coating disrupted the bacterial membrane and increased the oxidative stress in the bacteria. The Zn-MAO coating with 0.1Zn showed optimal cytocompatibility and antibacterial effects. Thus, the study demonstrated that micro-arc oxidation can produce Zn-doped TiO_2 coatings on titanium implants which have enhanced the bioactivity to improve the osseointegration along with having strong antibacterial properties to prevent implant infections.

In vivo with coated implants

While *in vitro* studies have demonstrated the benefits of TiO_2 and Al_2O_3 coatings, data from *in vivo* studies on the performance of coated implants is limited. However, the available evidence suggests that the coatings can improve the clinical outcomes.

One of the recent clinical studies on TiO_2 coated implants was conducted by Mollabashi et al. [69]. They evaluated the efficacy of TiO_2 coated stainless steel orthodontic wires in reducing *Streptococcus mutans* adhesion and preventing white spot lesions, a common side effect of orthodontic treatment. Sixty-eight (68) patients aged 12-25 years were recruited and divided into 4 equal groups based on duration of wire use - 1 week, 2 weeks, 3 weeks and 4 weeks. Within each patient's mouth, the TiO_2 coated wires were randomly assigned to one jaw while the uncoated control wires were placed in the opposite jaw. This allowed for the direct comparison of the bacterial adhesion between the coated and uncoated wires for each timeframe. The key clinical finding was that the *S. mutans* colony counts were significantly lower on the TiO_2 coated wires compared to the uncoated wires at 1-week post-insertion (Figure 6). This clearly demonstrated that the TiO_2 coating was effective in reducing the initial *S. mutans* adhesion and accumulation on the wire surfaces. However, no significant difference in the *S. mutans* counts was observed between the coated and uncoated wires from 2-4 weeks. This indicates that the anti-adhesion effects decreased over time, likely due to the gradual abrasion of the coating. By limiting the early *S. mutans* colonisation, the TiO_2 coating can still play a useful role in minimising white spot lesion risk

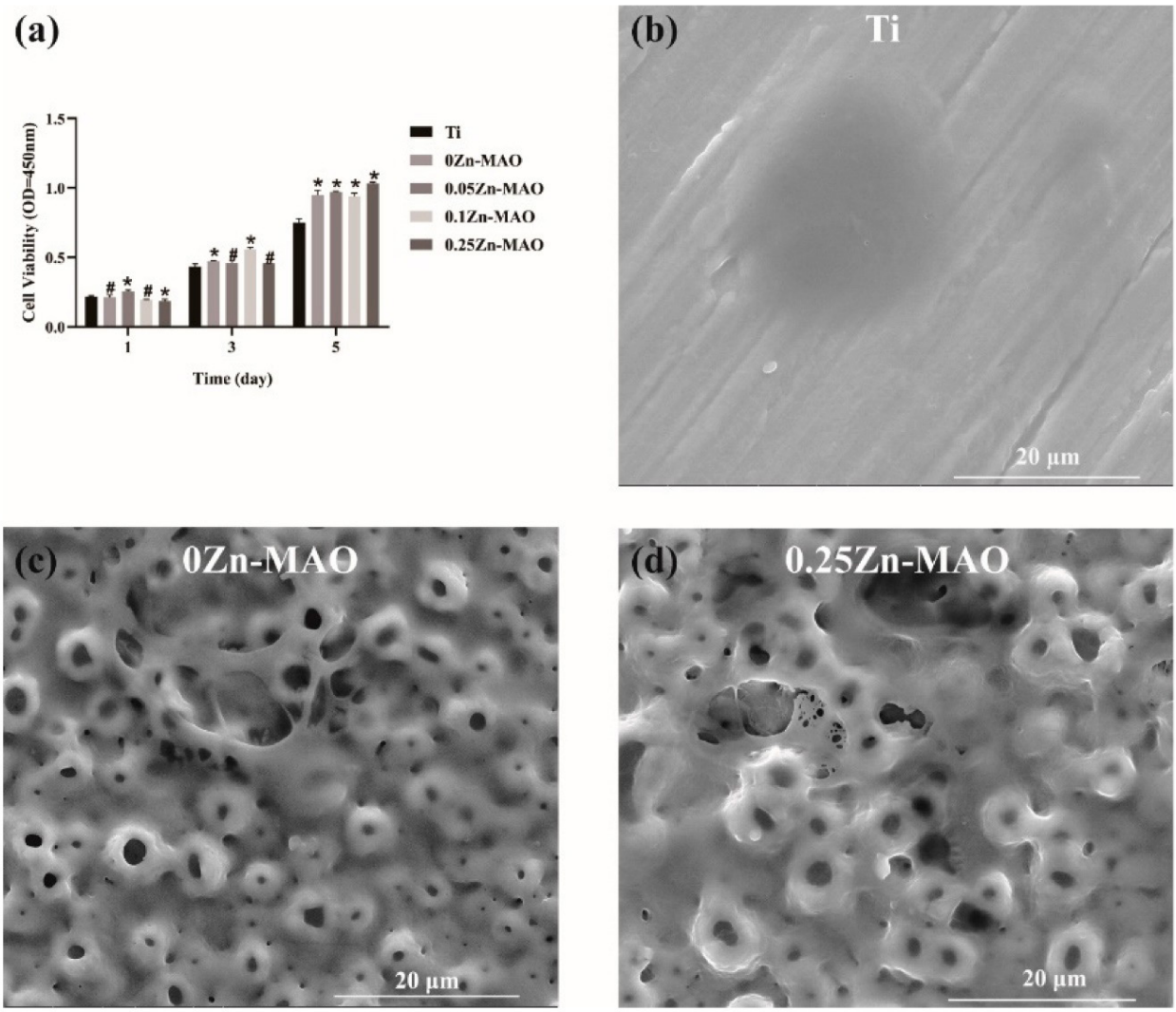

Figure 5. The cell biocompatibility of Zn-MAO (a). Cytotoxicity was measured after 1, 3, and 5 days of culture. The bone marrow mesenchymal stem cell (BMSC) morphologies on Ti (b), 0Zn (c), and 0.25Zn (d) groups surface for 3 days under SEM. Data are presented as mean ± SD; (* $p < 0.05$, # $p > 0.05$, vs. Ti group) [68]. Copyright 2023, MDPI.

during the initial stages of orthodontic treatment when the enamel is most vulnerable.

More recently, Chee et al. [70] investigated the effect of a nano-ceramic TiO_2 coating applied via atomic layer deposition (ALD) on the colour of a polymethyl methacrylate (PMMA) denture base material. The clinical perception and acceptance of the colour changes were also examined. Thirty PMMA specimens in three shades (light pink, original, dark pink) were fabricated, with ten specimens per shade coated with 30 nm of TiO_2 using ALD. The colour was measured before and after coating using a spectrophotometer. The colour difference (ΔE00) was calculated and compared to establish perceptibility (1.71 ΔE00) and acceptability (4 ΔE00) thresholds. In the clinical study, 10 patients and 14 prosthodontists evaluated the three PMMA shades before and after the TiO_2 coating. They rated their perception of the colour difference and satisfaction with the colour match on the visual analogue scales. The results showed that TiO_2 coating resulted in statistically significant colour changes for all three PMMA shades, with the ΔE00 values exceeding the 1.71 perceptibility threshold. However, the values were below the 4 ΔE00 acceptability threshold. In the clinical study, 77-83 % of the patients perceived a colour difference after the TiO_2 coating, while 69-96 % of the clinicians were satisfied with the colour match. The percentages of clinicians satisfied with the colour match were 96.4 %, 80 %, and 69.2 % for the light, original, and dark pink PMMA, respectively. The clinical findings suggest that while a colour difference was perceived after the TiO_2 coating, it was within an acceptable range, particularly for the lighter PMMA shades. Laypeople tended to notice the colour change more than clinicians.

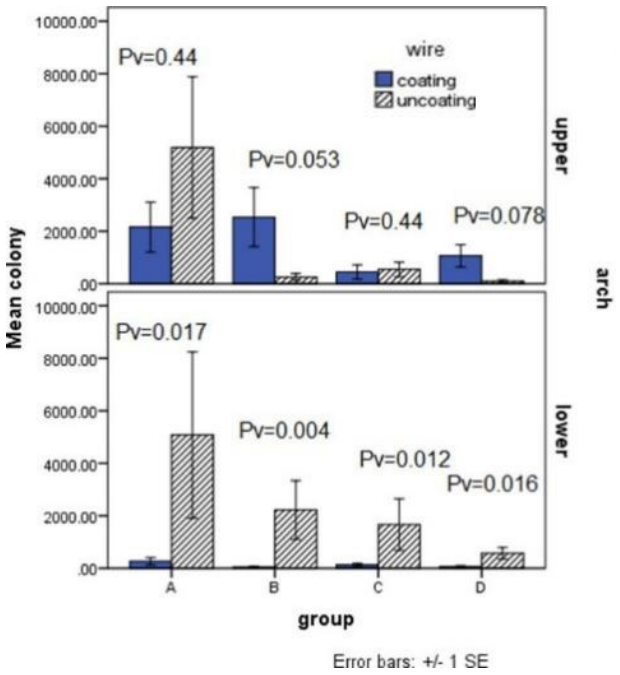

Figure 6. Comparison of Streptococcus mutans colonies by the upper and lower arch [69]. Copyright 2023, Taylor & Francis.

For the Al_2O_3 coated implants, a clinical study compared the performance of the diamond-like-carbon (DLC) coated femoral heads versus the Al_2O_3 ceramic femoral heads, when articulating with polyethylene (PE) cups in total hip arthroplasty (THA) [71]. A total of 202 patients received the cementless THA with either DLC/PE bearings (101 patients) or Al_2O_3/PE bearings (101 patients). The two groups were matched for age, weight, gender and indications for THA. After a mean follow-up of 8.5 years, the implant survival was significantly lower in the DLC/PE group, with only 54 % surviving compared to 88 % in the Al_2O_3/PE group. The Al_2O_3 ceramic femoral heads articulating with PE cups showed excellent clinical performance, with an 8-year implant survival rate of 88 %. In contrast, the DLC coated femoral heads articulating with PE had very poor results, with a high failure rate of 46 % at 8 years due to aseptic loosening requiring revision surgery. The analysis of 19 retrieved DLC heads by scanning electron microscopy revealed small defects and delamination of the DLC coating on the surfaces. This coating damage led to excessive wear of the PE inlay and, in some cases, the metallic substrate of the femoral head. Despite promising wear simulation studies showing good tribological properties of DLC, this clinical study found unacceptable high failure rates with DLC coated femoral heads in the THA. Al_2O_3 ceramic-on-PE bearings demonstrated significantly better implant survival compared to the DLC-on-PE bearings. The Al_2O_3/PE THA had good clinical outcomes with 88 % survival at 8.5 years. In contrast, DLC/PE had an extremely high failure rate of 46 % by 8.5 years due to delamination and defects in the DLC coating causing excessive wear. Although DLC coatings have favourable tribological properties in simulator studies, this did not translate to good clinical performance.

While the available clinical data is limited, the studies suggest that TiO_2 and Al_2O_3 coatings can improve the performance of orthopaedic implants in patients. The coatings appear to enhance osseointegration, reduce implant loosening and osteolysis, and improve the functional outcomes. However, larger and longer-term clinical trials are needed to validate the benefits of oxide coatings and determine their impact on implant survival and revision rates. More research is also required to optimise the coating properties for maximum clinical efficacy.

There are also some potential complications and failure risks associated with the coatings. Coating delamination or detachment from the implant surface is a possible complication. This can occur due to the inadequate adhesion of the coating to the substrate, mechanical stresses during implantation, and corrosive body fluids over time [72]. Delamination can expose the bare metal surface and compromise the benefits of the coating [73, 74]. However, most studies report good adhesion of TiO_2 and Al_2O_3 coatings deposited

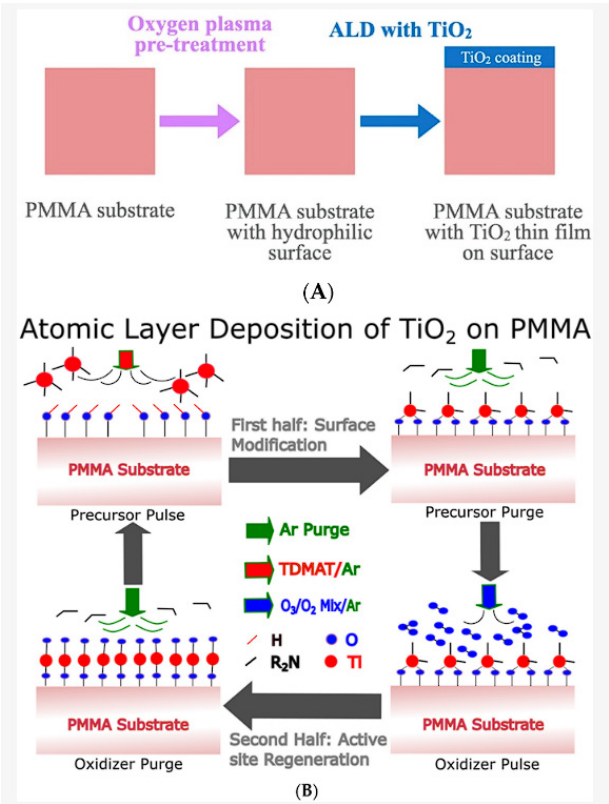

Figure 7. (A) Nano-coating of a PMMA specimen by Atomic Layer Deposition. (B) Schematic of the ALD reaction on the O-plasma treated PMMA using Tetrakis(dimethylamino) titanium (TDMAT) and O3/O2 mixture [70]. Copyright 2023, MDPI.

by modern techniques. Coating fracture is another potential complication, especially for thicker coatings [75, 76]. Cracks and fractures in the coating can serve as pathways for body fluids, reducing the corrosion resistance and compromising osseointegration [77]. While TiO_2 and Al_2O_3 coatings are generally resistant to fracture, optimisation of coating deposition parameters is needed to minimise this risk [78]. Wear and abrasion of the coating over time can expose the implant metal and reduce the service life of the coated implant. However, TiO_2 and Al_2O_3 coatings have been shown to be resistant to wear due to their hardness and smoothness [79, 80]. Appropriate coating thickness and mechanical properties are important to withstand long-term wear [81]. Cytotoxicity and adverse tissue reactions are possible, though most studies report that TiO_2 and Al_2O_3 coatings exhibit good biocompatibility [82]. The strict control of coating composition and properties is needed to minimise these risks. Data on failure rates of coated implants from long-term clinical studies are limited. The available evidence suggests that TiO_2 and Al_2O_3 coatings can reduce implant loosening and revision rates, though larger trials are needed for validation. Failure rates comparable to uncoated implants have been reported in some studies.

Comparison of TiO_2 and Al_2O_3 coatings

Both TiO_2 and Al_2O_3 coatings can improve the performance of orthopaedic implants. However, there are some key differences between the two coatings that determine their relative advantages and ideal applications:

Both TiO_2 and Al_2O_3 coatings have been shown to enhance the corrosion resistance of implants by acting as a physical barrier. However, TiO_2 coatings tend to provide better corrosion resistance due to their more stable oxide structure and ability to seal defects [83, 84]. This makes TiO_2 more suitable for load-bearing implants that require high corrosion resistance.

Both TiO_2 and Al_2O_3 coatings can improve the wear resistance of implants by forming a hard and smooth surface. However, Al_2O_3 coatings tend to be harder and thus provide better wear resistance [85, 86]. This makes Al_2O_3 more suitable for implants subjected to high friction and wear, like hip and knee replacements.

TiO_2 coatings show stronger antibacterial effects than Al_2O_3 coatings, particularly under UV light irradiation due to photocatalysis [87–90]. This makes TiO_2 more suitable for implants where infection risk is high. Both TiO_2 and Al_2O_3 coatings exhibit good biocompatibility and cytocompatibility. However, Al_2O_3 coatings tend to be more stable and less reactive, resulting in lower risks of cytotoxicity [91, 92]. This makes Al_2O_3 more suitable for implants where biocompatibility is critical.

Challenges and future directions

Limitations of the current coatings and technologies

While TiO_2 and Al_2O_3 coatings have shown promise in improving orthopaedic implant performance, there are still several limitations of the current coating technologies:

Lack of long-term data: Most studies on coated implants have follow-up periods of only 1-5 years. There is a lack of data on the long-term performance, stability and failure rates of coated implants over 10-20 years. Such long-term clinical data are needed to validate the true benefits of oxide coatings. The impact of coatings on the implant survival and revision rates should be investigated. This is the most important metric to establish the clinical benefits of coatings. However, current short-term studies are insufficient to determine if coatings can significantly reduce the revision rates over the lifespan of the implants.

Variability in coating properties: There is significant variability in the properties of TiO_2 and Al_2O_3 coatings deposited by different techniques. Properties like the thickness, roughness, adhesion and composition can vary widely, making it difficult to compare results across studies. The standardisation of the coating properties is needed.

Suboptimal coating design: Most current coatings use simple single-layer TiO_2 and Al_2O_3 designs. There is a need for more sophisticated multilayer, graded and composite coatings that can achieve optimised combinations of properties.

Limited antibacterial efficacy: While TiO_2 coatings show some antibacterial effects, their efficacy is still limited. There is a need for coatings with stronger and more reliable antibacterial properties to reduce infections.

Difficulty in coating complex implants: Many coating techniques still struggle to achieve uniform coverage of complex, three-dimensional implant shapes. Better methods are needed for coating complex geometries.

High costs: The costs of coating technologies and coated implants are still relatively high. There is a need for lower-cost coating methods to enable wider clinical adoption.

Environmental impact: Some coating techniques rely on vacuum systems and organic solvents, posing environmental risks. More sustainable and eco-friendly coating methods are needed.

Potential for multifunctional and smart coatings

While the current TiO_2 and Al_2O_3 coatings have shown promise, there is significant potential to develop next-generation multifunctional and smart coatings for orthopaedic implants:

Multilayer and graded coatings: By combining TiO_2, Al_2O_3 and other materials in multilayer or graded designs, coatings with optimised combinations of properties like corrosion resistance, wear resistance, osseointegration and antibacterial effects can be achieved. This could enable coatings tailored for specific implant applications. Composite coatings: Incorporating fillers like hydroxyapatite, silver nanoparticles and antibiotics into TiO_2 and Al_2O_3 coatings can endow them with enhanced osseointegration, antibacterial and drug-eluting capabilities. This could enable coatings with multifunctional performance.

Nanostructured coatings: Developing TiO_2 and Al_2O_3 coatings with nanostructured surfaces and controlled release of nanoparticles can improve properties like osseointegration, antibacterial effects and drug delivery. This could enable next-generation high-performance coatings.

Self-healing coatings: Incorporating microcapsules containing healing agents into coatings can enable self-healing of cracks and defects over time. This could significantly improve the coating stability and durability.

Stimuli-responsive coatings: Developing coatings that can respond to external stimuli like light, temperature, pH or magnetic fields could enable on-demand drug release, antibacterial activation and other smart functions.

3D-printed coatings: Advances in 3D printing of oxide materials could enable the development of coatings with complex 3D geometries tailored for specific implants. This could improve the coating uniformity on complex implant shapes.

CONCLUSION

This comprehensive review analyses the current status of TiO_2 and Al_2O_3 ceramic coatings for orthopaedic implants. Magnetron sputtering and micro-arc oxidation are the most widely used deposition methods, with each having their own unique advantages and limitations. Extensive data from corrosion, wear, antibacterial, and cell culture studies demonstrate TiO_2 coated implants exhibit superior surface properties compared to uncoated Ti, Co-Cr, and stainless steel implants. TiO_2 coatings also appear to promote osseointegration in vitro. Al_2O_3 coatings significantly improve the wear resistance and corrosion protection of alloy implants. However, long-term clinical studies proving reduced revision rates for TiO_2 or Al_2O_3 coated implants remain sparse. While both coatings offer benefits, TiO_2 seems better suited for titanium implants where osseointegration is desired, whereas Al_2O_3 provides a bioinert surface for alloy implants. Composite coatings combining TiO_2 and Al_2O_3 need further investigation. The current challenges facing adoption include coating stresses, thickness uniformity, coating complex geometries, durability concerns, and lack of sufficient clinical data. Future efforts should focus on developing innovative deposition processes, mechanistic and large-scale clinical studies, and cost-benefit analyses. Overall, TiO_2 and Al_2O_3 represent a promising coating platform for the next generation of high-performance orthopaedic implants.

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