

ADVANCING IN THE QUEST FOR SMARTER IMPLANTS: A BIOACTIVE AND ANTIBACTERIAL PLASMA SPRAYED COATING ON BIOCOMPATIBLE POLYMERS

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ABSTRACT

The use of polymers in the field of orthopedics and tissue engineering is leading to new frontiers in its applications. Usually, it is desired for implants to support bone in-growth and to enhance osseointegration as well as to avoid post-surgical complications like bacterial infections. When these requirements are met, new advances in the quest for smarter implants can be achieved. Being Atmospheric Plasma Spray (APS) the most widely used technology for surfacing metal implants, the coating of polymers is a step towards the goal for smarter implants. Nonetheless, plasma sprayed coatings have not been widely studied on polymers. Therefore, the aim of this study was to plasma spray polymer samples with bioactive and antibacterial materials, in order prove their viability, and analyze their micro-structure and stability, as well as determine their equivalence with plasma sprayed coatings over metals. Characterization of samples was performed using visual inspection and scanning electron microscopy. Results indicate comparable outcomes with plasma sprayed coatings over metals, proving the viability for bioactive and antibacterial plasma sprayed coatings over polymers. Also, bone cells adhesion to the treated samples show the clinical potential in the quest for smarter biomaterials.

1. Introduction

The use of polymers in modern medicine plays an important role. Advantages like their low specific weight, cost, and performance, has led to new frontiers regarding applications and patient customization in the field of orthopedics and tissue engineering [1,2]. Usually, it is desired for implants to support bone in-growth and to enhance osseointegration with the remaining bone or tissue structure, as well as to avoid post-surgical complications like bacterial infections [3]. When the combination of material, bioactivity and antibacterial properties is met, new advances in the quest for smarter implants can be achieved. To accomplish this purpose, these medical devices can be coated with different materials through technologies like thermal spray. Among different thermal spray techniques, Atmospheric Plasma Spray (APS) is the most widely used technology for surfacing implants [3-7]. Nevertheless, plasma sprayed coatings have been primarily applied to metallic substrates, and unfortunately, only a few studies are available on polymers and composite materials [8]. Therefore, the aim of this study was to coat polymeric samples with bioactive and antibacterial materials. Polymeric substrates chosen were poly-ether-ether-ketone (PEEK), polylactic acid (PLA) and polyvinyl alcohol (PVA), which are commonly used in orthopedics and tissue engineering applications [1,9,10].

The coating materials used in this work were selected in the one hand to promote bioactivity in the surface of the substrate, and on the other hand, to avoid bacterial propagation at a lower cost than silver ions and nanoparticles [11]. Regarding bioactive materials, hydroxyapatite (HAp, $[\text{Ca}_5(\text{PO}_4)_3\text{OH}]$) is a widely-known mineral that promotes osseointegration [12], and titanium dioxide is often sprayed on titanium alloy implants to build apatite similar to the bone in the surface, improving the adhesion force between

the implant and the bone [5]. Furthermore, titanium dioxide (TiO_2) also has also been reported to have antibacterial properties [11]. Copper (Cu) was also used as antibacterial material for the experiments, which along with zinc, hold a promise as potent antibacterial agents on a wide spectrum of bacterial species [11].

Due to the physics and experimental nature of the APS process, and the few references about plasma sprayed coatings over polymers, the experimentation was conducted first based on an empirical basis to determine adequate parameters to obtain appropriate coatings. In this case, coatings were evaluated in terms of substrate shape (non-deformation of the polymeric probes), stability and morphology of the coating (macro and micro analysis); using simple visual characterization (20 cm from sight) and scanning electron microscopy (SEM) imaging. The main goal of the study was to obtain depositions over polymers that are equivalent to depositions over metals, mostly in the terms of their microstructure.

2. Materials and methods

2.1. Test materials

High purity biocompatible hydroxyapatite (Oerlikon MetcoTM 6902 Hydroxylapatite) was used, with particle size between 50 and 160 μm , and at least 95% calcium phosphate.

The titanium dioxide used (Sulzer MetcoTM AmdryTM 6505) had a chemical composition of (wt. %) 99.0 TiO_2 , <0.2 TiO_2 , <0.2 Fe_2O_3 , <0.2 SiO_2 , and <0.5 of other elements. Particle size was reported by vendor as 45 +/- 5 μm .

For the antibacterial coatings, a mix of 97 wt.% hydroxyapatite (MetcoTM 6902) and 3 wt.% copper

Metco™ 55 was used. The powder was treated using a mixer for two hours and dried at 60 °C for 12 hours. The copper used is classified as pure metal, copper base powder, with chemical composition of 99.0+ wt.% Cu, and <0.7 (maximum) of other elements. The nominal particle size distribution reported by the vendor was 90+/- 38 μm.

The substrate materials were 11 mm diameter discs of PEEK, PLA and PVA. The PEEK was cut from a 1 mm thickness sheet of semi-crystalline condition. PLA and PVA discs were obtained by a 3D printer, from a EasyFil™ PLA and AquaSolve™ PVA spools, respectively, both in natural color.

2.2. Equipment used and experiment setup

The plasma spray equipment used –located at the Leibniz Institute for Plasma Science and Technology (INP Greifswald), Germany– was Oerlikon Metco™ System Platform MultiCoat™, with one F4MB-XL plasma torch. For the HAp and HAp+3 wt.% Cu coatings, plasmatron power was set at around 24 kW, while for the TiO₂ coatings, power was set near 45 kW.

Substrates were placed at different stand-off distances (distance from the exit of the plasma torch to the surface to be coated) to evaluate their shape after exposure to the high temperature plasma, as well as the coating apparent adherence to the substrate. This is, the formation of a closed layer (substrate completely covered) or an open layer (substrate can be seen). Also, the quantity of layers and the cooling time between each coating, were characteristics taken into consideration.

Additionally, the influence of the roughness of the substrate was tested. Corundum blasting (tiny alumina pellets) was applied to some substrates,

while others maintained their natural finish. To test coating stability, the probes were placed in ultrasonic bath with ultrapure water, for 15 minutes.

The microstructure, chemical composition and wettability of the coating are key factors for a proper adhesion of the bone tissue in the surface of implants. To test the bioactivity of the coatings, bone cells (osteoblasts MG63) were cultured over the PEEK substrates coated with TiO₂+HAp, for one hour on a 2.5% SBF serum and 50,000 cells/600 microliters.

2.3. Characterization methods

Visual characterization with no magnification, at 20 cm from the eye was performed to evaluate coating macrostructure (closed or open layer), and changes in color and shape of the of the substrate. For sputs microstructure, coating stability and adhesion evaluation of MG63 osteoblasts, a Hitachi TM-1000 scanning electron microscope (SEM), with acceleration voltage of 15 kV, was used. For roughness characterization, profilometer Zeta-20 from Zeta Instruments, was used.

3. Results and discussion

Overall, the best deposition results were obtained for the PEEK substrates, due to its higher melting point compared to PLA and PVA, making it easier to deposit several layers in order to accomplish a high-quality coating. Also, there was no appreciable deformation or temperature damage of the substrate itself.

Regardless of the stand-off distance used and even with only one layer deposited, PLA and PVA

substrates showed some degree of deformation after exposure to the plasma spray, as well as some burning marks and blisters, as shown in Figure 1. Figure 1(a) shows the case of the PVA substrates, whereas Figure 1(b) the PLA substrates. The latter were more significantly damaged by the temperature of the plasma spray. Therefore, the focus of



Fig. 1. Deformation presented in samples after exposed to high temperature plasma: (a) PVA substrates, (b) PLA substrates

the study from here onwards relies on depositions over PEEK substrates.

One of the most important results obtained, is that when applying a TiO₂ layer prior to the application of HAp, the former creates a good bonding layer for the HAp to adhere to the substrate. The outcome, as shown in Figure 2, is a closed deposited layer, where the substrate surface totally covered, giving better results than when applying even more layers exclusively of HAp. Figure 2(a) shows the case of a deposition of 10 passes of HAp with no prior TiO₂ deposition. An open area in the deposition in the upper left corner can be observed as a darker color. Figure 2(b) shows the case of a deposition of 2 passes of TiO₂ prior to 6 passes of HAp, and Figure 2(c) of 2 passes of TiO₂ prior to 4 passes of HAp. In both cases a closed deposition was achieved.

Also, the effect of substrate preparation on adherence properties, roughness in this case, was evaluated. Figure 3 shows samples sprayed under the same conditions, but with different surface roughness: column (a) corresponds to PEEK substrates without any treatment (“Polish”) and an average roughness $R_a=1,86 \mu\text{m}$, while column (b) displays substrates treated with corundum blasting (“Rau”) and average roughness $R_a=4,29 \mu\text{m}$. It is clear how all the samples shown by Figure 3(a) retain less coating material than samples with rougher surface, as



Fig. 2. Deposition difference when applying TiO₂ as a bonding layer before HAp deposition. (a) No TiO₂ applied as bonding layer and 10 layers of HAp, open coating in the upper left corner (b) 2 layers of TiO₂ prior to 6 layers of HAp, closed coating (c) 2 layers of TiO₂ prior to 4 layers of HAp, closed coating.

shown by Figure 3(b).

One important consideration when depositing HAp by thermal spraying, is to make sure that it does not decompose into undesired dehydroxylated phases due to the hot plasma jet, such as oxyhydroxylapa-

tite (OHA) and oxyapatite (OA), as well as thermal decomposition products such as tri-(TCP) and tetra-calcium phosphates (TTCP), and quenched phases such as amorphous calcium phosphate (ACP) [6]. Therefore, in order to confirm that HAp did not decompose and kept a phase mostly crystalline after high thermal exposition, an X-ray Diffraction (XRD) analysis was conducted ($15^\circ < 2\theta < 68^\circ$, scan step time 13.77 s, generator settings 45 kV and 40 mA, CuK_α radiation), were the HAp spectra obtained after deposition was compared to a HAp powder spectra prior to deposition, as shown in Fig. 4. It is seen that both spectra are practically identical, demonstrating that HAp conserves its chemical structure and composition after spraying (Fig. 4(b)). As mentioned, the main goal of the study was to obtain equivalent micro-structures on the plasma sprayed polymers, when compared to plasma sprayed metal substrates reported by other authors, like Heimann [10] (Fig. 5), Demnati et al. [5] and Dey and Mukhopadhyay [6]. Thus, scanning electron microscopy (SEM) was

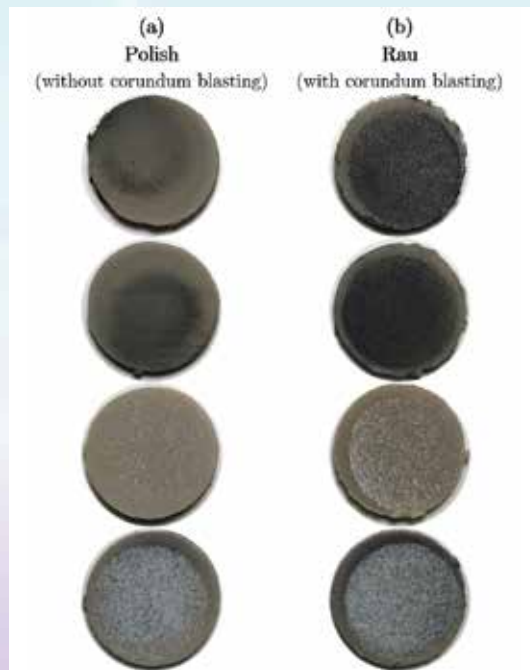


Fig. 3. Comparison of PEEK substrates with different depositions, regarding surface preparation and deposited material adherence: (a) substrates without any treatment ("Polish"), (b) substrates treated with corundum blasting ("Rau").

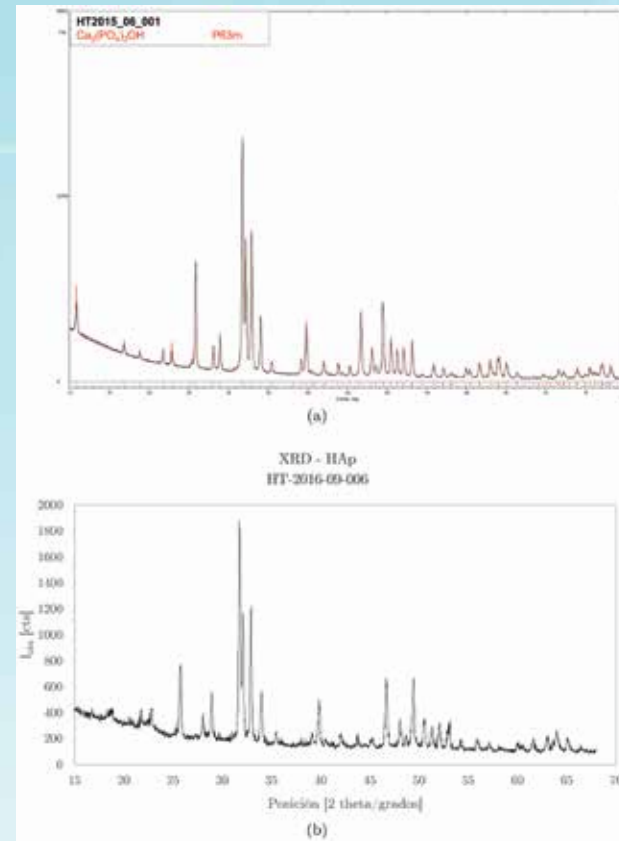


Fig. 4. HAp XRD spectra comparison: (a) HAp powder prior to deposition, (b) HAp deposited (plasma sprayed), where well defined peaks denote a phase mostly crystalline and high similarity with the spectra shown in (a).

carried out for different depositions and the respective images are shown in Figure 6 in.

For HAp deposition only on PEEK, Figure 6(a) shows overlapped and properly melted splats, without significant porosity. For the deposition of TiO_2 +HAp, shown in Figure 6(b), properly developed splats are seen, but also some micro-porosity is exhibited, as shown by the arrow. This porosity is a product of high viscosity in the HAp, which reveals not enough enthalpy was applied in the sprayed particles for the HAp to reach the ideal molten state before impacting the surface.

Figure 6(c) displays the antibacterial deposition of TiO_2 +HAp+3 wt.% Cu, where it is shown how the

copper particles, in brighter contrast, were properly molten and overlapped with the HAp rich regions. In general, one can confirm the similarities of the coating SEM images with the studies on metals of

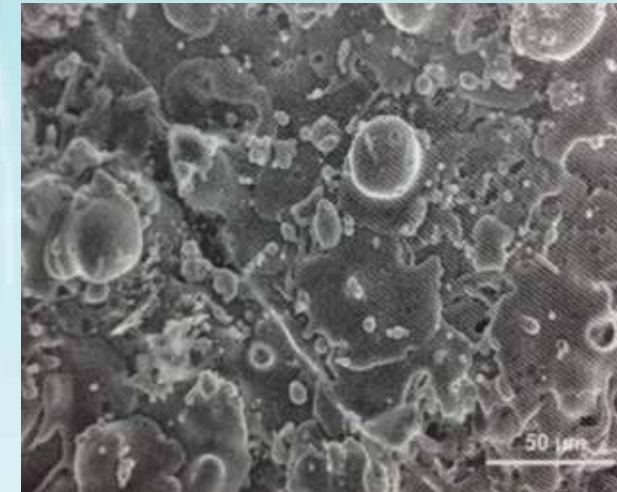


Fig. 5. Typical SEM image of plasma sprayed HAp coating, over a metal substrate, presented by Heimann [5]. The image shows well developed and overlap splats, with some loosen particles in the surface that did not reach complete melting.

the above-mentioned authors, like the one shown at Fig. 5, as well as with some of the available polymer substrates studies [8,15,16].

Regarding the coating stability tests, samples were placed in an ultrasonic bath using ultrapure water for 15 minutes. SEM imaging, is exhibited in Figure 7. Figure 7(a) shows the case for HAp deposition, Figure 7(b) the TiO_2 + HAp deposition and Figure 7(c) the TiO_2 +HAp+3 wt.% Cu deposition. The images show that the coatings were stable in the three cases studied, but sharp edges and big pores, left by washed big particles, are revealed. The pores are indicated by arrows in the respective figures.

MG63 osteoblasts were cultured in PEEK samples with TiO_2 +HAp and TiO_2 +HAp+3 wt.% Cu deposition, to prove if any cell adhesion would be possible, since PEEK is a bioinert material. As it is seen in Figure 8,

cells (pointed by arrows) started to grow over the HAp surface in (a) and even at the surface containing copper in (b), after just one hour of culture. This, is evidence for a successful implantation of a possible bone implant in the future.

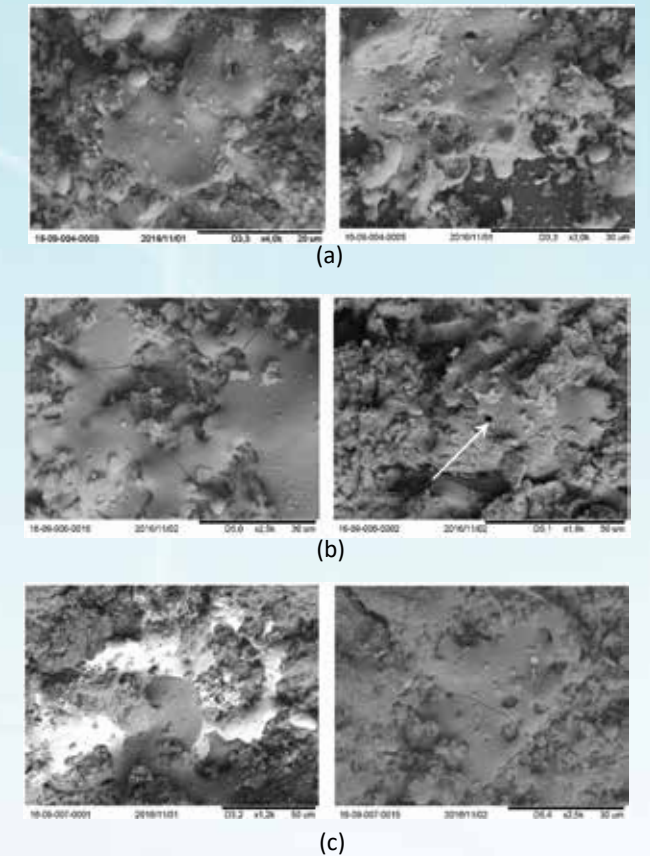


Fig. 6. (a) HAp deposition over PEEK substrate, with overlapped and properly melted splats. (b) TiO_2 +HAp deposition, with well-developed splats and some micro-porosity product of high viscosity HAp. (c) TiO_2 +HAp+3 wt.% Cu deposition, where both copper (brighter contrast) and HAp particles are well deposited.

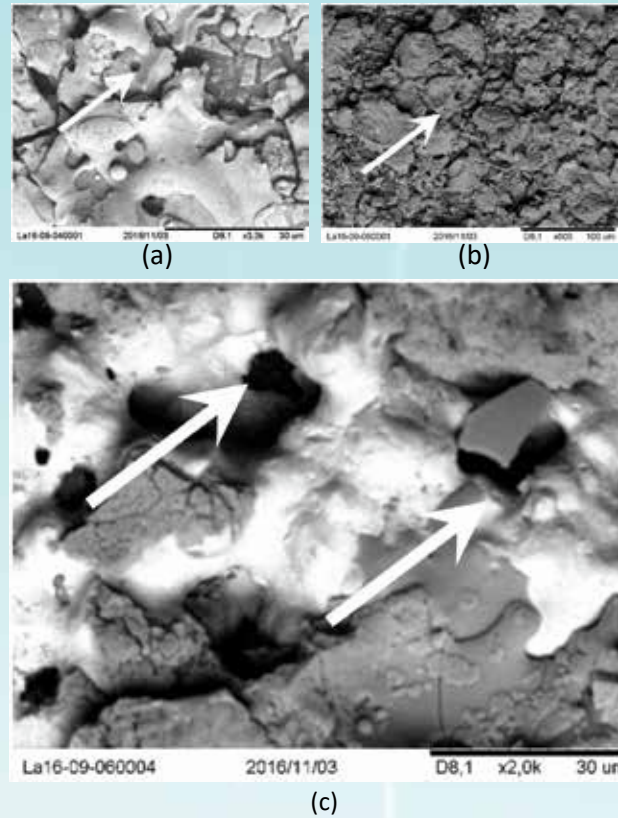


Fig. 7. Plasma spray coated samples after ultrasonic bath. (a) HAP deposition, (b) TiO₂+HAp deposition, (c) TiO₂+HAp+3 wt.% Cu deposition.

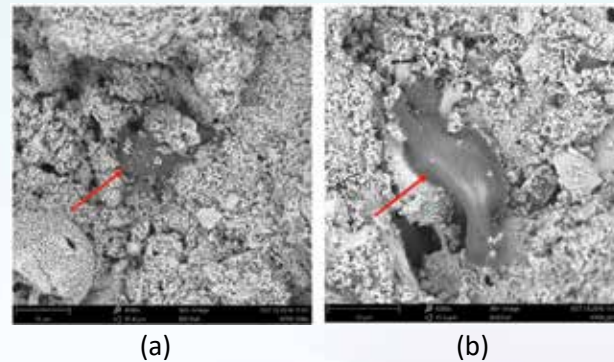


Fig. 8. SEM imaging of MG63 osteoblasts (pointed with arrows, darker contrast) growing on PEEK substrates, coated with (a) TiO₂+HAp, and (b) TiO₂+HAp+3 wt.% Cu.

4. Conclusions

Overall, the results show comparable outcomes with the reported by other authors for plasma sprayed coatings over metals, proving the viability for bioactive and antibacterial plasma sprayed coatings over polymers, especially in high temperature thermoplastics like PEEK. For low melting point polymers like PVA and PLA, it is recommended to experiment with other different parameters and preferably, with a low energy plasma spray system (LEPS), to avoid substrate damage. Furthermore, the coatings over PEEK show good adherence to the substrate after a simple stability test, since they keep most of the micro-structure seen before the ultrasonic bath. Additionally, the growth of bone cells in the samples show the clinical potential of the presented combination of bioactive coatings and polymers, opening interesting opportunities in the field of orthopedics and tissue engineering.

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