Influence of substrate metal alloy type on the properties of hydroxyapatite

coatings deposited using a novel ambient temperature deposition technique

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Abstract

Hydroxyapatite (HA) coatings are widely applied to enhance the level of osteointegration onto orthopaedic implants. Atmospheric plasma spray (APS) is typically used for the deposition of these coatings, however HA crystalline changes regularly occur during this high thermal process. This paper reports on the evaluation of a novel low temperature (<47 °C) HA deposition technique, called CoBlast, for the application of crystalline HA coatings. To-date, reports on the CoBlast technique have been limited to titanium alloy substrates. This study addresses the suitability of the CoBlast technique for the deposition of HA coatings on a number of alternative metal alloys utilised in the fabrication of orthopaedic devices. In addition to titanium grade 5, both cobalt chromium and stainless steel 316 were investigated. In this study HA coatings were deposited using both the CoBlast and plasma sprayed techniques, and the resultant HA coating and substrate properties were evaluated and compared. The CoBlast deposited HA coatings were found to present similar surface morphologies, interfacial properties and composition irrespective of the substrate alloy type. Coating thickness however displayed some variation with the substrate alloy, ranging from 2.0 to 3.0 µm. This perhaps is associated with the electro-negativity of the metal alloys. The APS treated samples exhibited evidence of both coating, and significantly, substrate phase alterations for two metal alloys; titanium grade 5 and cobalt chrome. Conversely, the CoBlast processed samples exhibited no phase changes to the substrates after depositions. The APS alterations were attributed to the brief, but high intensity temperatures experienced during processing.

Keywords: Low temperature depositions process, Deposition of crystalline hydroxyapatite coatings, Metal alloy substrate evaluations, Thermally affected substrates, Residual alumina grit.

1 Introduction

Hydroxyapatite (HA) is a calcium phosphate apatite which has a chemical composition similar to the mineral phase of naturally occurring bone and is classified as osteo-conductive $^{1-5}$. These attributes have led to the broad application of HA in both the orthopaedic and dentistry fields $^{3-6}$. Despite its biological properties however, the bulk mechanical properties of HA are inadequate for load bearing applications $^{1.5}$. In its bulk form HA is brittle, has poor tensile strength and low impact resistance $^{1.5}$. Consequently HA is more often used as a coating to enhance the biological response of orthopaedic implants, while the durability and mechanical functionality is retained in the device's metallic substrate $^{1.2.7}$.

The metal alloys typically used in the fabrication of cement-less orthopaedic implants are; titanium grade 5, stainless steel 316 and cobalt chrome ^{1.8.9}. The HA coating of such implants are typically performed using a thermal spray technique called atmospheric plasma spray (APS) ^{5.6.10,11}. The ability to deposit HA onto a broad range of metal alloy substrates is an important feature of the APS technique, making this an important processing consideration for any alternative deposition technology. A concern with the APS technique for HA coating deposition however, is the high residual stresses within the coatings, as well as uncontrolled changes in HA crystallinity that can occurs during the high temperature deposition process (approx. 6000K) ^{1.5,11-16}. For example if a reduction in HA crystallinity occurs, it can result in coatings with higher dissolution rates (ie increase material lose) and thus reduced long term fixation *in vivo* ^{1,17,18}. Further to this, reports have suggested that this type of thermal deposition process can significantly affect the substrate properties ^{16,19,21}. As a consequence, there has been increased interest in alternative deposition techniques, which minimize the thermal impact on both the powder and substrate material ¹¹.

This paper reports on a recently developed microblasting technique for the application of HA coatings onto metallic substrates called CoBlast ²². The CoBlast technique utilises two particle jets

entrained in dry compressed air, one consisting of HA particles and the second, particles of a suitable abrasive media. These jets coincidently impinge on a point at the substrate surface resulting in the deposition of a HA coating. To date reports on the CoBlast HA deposition process have focused primarily on titanium and its alloys ²³⁻²⁹. The aim of this research is to investigate the potential of the CoBlast HA deposition technique for use with a broader range of metal alloys, specifically: cobalt chrome and stainless steel 316. Furthermore, the substrate-HA interface of the CoBlast treated samples will be benchmarked against those obtained using the APS process for the same metal alloy substrates.

2 Materials and Method

2.1 Materials and Sample preparation

HA powder with particle size in the range 25-60 μ m was purchased from S.A.I. (Science Applications Industries, France). To remove any retained moisture that may hinder powder flow, the HA powder was heated to 150°C for 1.5 hours prior to the deposition experiments. Al₂O₃ powder (with mean particle size of 100 μ m) was purchased from Comco (USA) and was utilised as an abrasive in conjunction with the HA for the CoBlast process.

The deposition studies were performed on circular coupons of titanium grade 5 (Ti), stainless steel 316 (SS) and cobalt chrome (CoCr) alloys, with diameters of approx. 20 mm and thicknesses greater than 5 mm. Prior to coating, the test substrates were polished with 1200 grit silicon carbide paper, followed by ultrasonic cleaning consecutively with methanol and acetone for 5 minutes each.

The APS HA coatings were obtained from a commercial supplier of coatings to the medical device sector. The depositions were carried out with the same HA powder and substrates as used with the CoBlast process. These coatings were found to have an average thickness of approx. 55 µm, which

was independent of the substrate alloy. This was to be expected as the thickness of is dependent of the number of deposition passes executed $\frac{1}{2}$.

2.2 Deposition equipment

The CoBlast deposition applicator (Figure 1) consists of the abrasive and HA jet applicator nozzles mounted in a sealed glove box, above an X-Y slide table. This facilitates motion of the substrates beneath the applicator, which coincidentally blasts the air jets, with entrained particles, at a point on the substrate surface. A containment bag encloses the working environment in which the deposition process is conducted. The HA and abrasive powders are delivered to an area on the titanium surface (or 'blast-zone') through the applicator nozzles using two Comco Accuflo powder feeders.



Figure 1: A) Schematic of the CoBlast deposition equipment, B) Schematic of the dual nozzle CoBlast applicator Preliminary deposition studies focused on optimising HA coating coverage and homogeneity. The optimised deposition conditions using both the HA and Al_2O_3 powder are given in Table 1. The coatings were applied by passing the prepared substrates through the coincident blast-zone, using a 2 mm raster pattern at ≈ 10 mm/s. Following CoBlast processing, the samples were immersed in deionised water and ultrasonically cleaned for 5 minutes to remove any residual non-adhered HA particles. The samples were then dried in an oven at 50 °C.

Powder	Mean Particle size (µm)	Nozzle Angle (°)	Height (mm)	Pressure (kPa)
HA	25-60	80	20	590
Al_2O_3	100	80	20	415

2.3 HA Coating and substrate analysis

A TM-1000 Hitachi scanning electron microscope (SEM), operating in back-scatter mode, was utilised to examine the coating morphologies and cross sections. Surface morphology and cross sectional images were taken at 8 random points on 3 samples of each coating. Digimizer software (MedCalc Software, Mariakerke, Belgium) was employed on the cross sectional images to facilitate HA coating thickness data to be obtained. The samples were prepared for cross sectional imaging by mounting in polyester resin blocks, cutting transverse sections and polishing the sections to a submicron finish.

A WYKO NT1100 optical profilometer, operating in vertical scanning interferometry (VSI) mode with a resolution of 3 nm per individual measurement, was utilised to measure the roughness component (R_a : Arithmetic average) of the HA coating. Measurements were taken at a magnification of x51.5, over 10 random areas (area dimensions: 120 x 91µm) on 4 samples of each HA coating type. To further facilitate the examination of the substrate under the CoBlast and APS HA coatings, the HA layers were removed by immersion in a 1M HCl solution for up to 3 minutes. Roughness measurements were obtained of the metal substrates after washing in deionised water followed by drying.

2.4 Chemical and crystallinity analysis

Elemental analysis was carried out using an EDX (Swift-ED, Oxford Instruments Analytical) module attached to the Hitachi SEM, operating at an acceleration voltage of 15kV and a magnification of x200. EDX was obtained for 8 random points on 3 samples of each coating, using a raster scan to obtain an average of elements present.

X-Ray Diffraction (XRD, Siemens D500 system) was performed to assess coating crystallinity. HA coatings deposited using both the CoBlast and APS technologies were analysed over the detector range of 25° to 35° with a resolution of 0.02° and a grab time of 3 seconds. The XRD scans were also carried out on compressed tablets of the HA precursor powder for comparison to the obtained HA coating spectra. In addition, XRD was performed over the detector range of 25° to 60° on the CoBlast and APS treated substrates after HCl etching (1 M), to examine each of the substrate metal alloys crystallography before and after the deposition treatements. MAUD (Materials Analysis Using Diffraction), a spectra fitting software, was utilised to evaluate the XRD spectra obtained for both the HA coatings and substrates $\frac{30.33}{2}$.

2.5 Mechanical Testing

Micro-hardness values for the three metal alloy substrates were obtained using a leitz Knoop indentor. A 5 N load was applied, via the Knoop diamond tip, into the substrate. A total of 5 indentations were performed per substrate, at a standard indentation period of 5 seconds. The width of the indentations was evaluated using an Olympus GX51 digital optical inverted microscope, and facilitated the determination of micro-hardness values for each of the substrates.

The adhesion of the CoBlast deposited coatings were assessed using a scratch testing technique, which involved pre-loading a Vickers diamond tip to 5 N on the coated surface, and gradually increasing the load (100 N/min) up to 120 N, while the tip traverses across the coating at 10 mm/min. This type of adhesion testing is performed typically on thin, smooth and uniform coatings such as those deposited using PVD, however, the scratch test is considered adequate for a comparative assessment of adhesion performance on coatings provided the comparison is between coatings deposited using the same technology ³⁴. The failure criterion for this test, occurred when complete removal of the HA material from the substrate surface was achieved. The total length of the scratch is term Total Scratch Length (SL_T) and the length to failure of the coating is termed Coating Scratch

Length (SL_C). It is the ratio of these components, SL_C/SL_T, multiplied by the change in force (Δ F, Max force – Pre-loaded force) which determines the Critical Failure Load (L_{CF}).

$$L_{CF} = (SL_C/SL_T) \times \Delta F$$

3 Results and Discussion

In this section the properties of the CoBlast HA coatings deposited on titanium grade 5, stainless steel 316 and cobalt chrome are firstly compared. Subsequently the focus is on benchmarking the CoBlast coatings with APS deposited HA coatings applied onto the same alloy substrates. The study included an investigation of coating morphology, their adhesion to the substrate surface, cross-sectional examination and phase/compositional analysis. An assessment of the substrate micro-hardness is also carried out.

3.1 Morphology and Substrate Microhardness

Figure 2A and B display typical coating morphologies (SEM) and line profiles (optical profilometry) for the CoBlast deposited HA coatings on the three metal substrates. The SEM micrographs indicate that the CoBlast deposited HA coatings exhibit similar morphologies irrespective of the substrate material. The line profiles (Figure 2B) however, suggest some variation exists between the coated substrates, with deeper indentations observed on the SS coated substrates, when compared to the CoCr and Ti coated substrates. These indentations are linked to the abrasive action inherent in the CoBlast process, due to impact and removal of material by the Al₂O₃ powder grains. To better understand these results, a comparative optical profilometry study was performed on both the coated and metal substrate after coating removal.



Figure 2: SEM images (A) and line profile scans (B) of the CoBlast HA coatings on the three metal substrates evaluated (Scale bar = $30 \mu m$)

Figure 3 and Figure 4 provide details on the roughness (R_a and R_t respectively) obtained for the CoBlast deposited HA coatings on the three substrate types. The R_a values were found to increase in the following substrate order: cobalt chrome < titanium < stainless steel. The HA coatings were removed by dissolution in 1M HCl. Figure 3 also provide details on the roughness data obtained for the substrates. The R_a values for the latter were slightly reduced when compared to their respective coated samples, but still followed a similar trend to that of the coated samples. Furthermore the roughness results validate the suggestion that the SS substrates were most affected by the abrasive action, as this substrate exhibited the highest roughness for both the coating and substrate. In order to investigate these micro-hardness measurements were carried out on each substrate to determine if substrate hardness had an influence on the roughness obtained after the CoBlast treatment.



Figure 3: Roughness (R_a) results for CoBlast deposited HA on the metallic substrates shown, also shown is the roughness of the substrate beneath after HA removal



The substrate microhardnesses results in Figure 5 were determined using the knoop indentation technique. The microhardness results demonstrated a close correlation with the substrate roughness, where a decrease in roughness was mirrored by an increase in microhardness. It is possible this relationship stems from the abrasive 'chipping action' functioning at the micron level, due to the

abrasive particle's size, where the microhardness might best represent the mechanical properties of the substrate at this level. This would explain why the material with the lowest microhardness, stainless steel, exhibited the roughest surface finish after the CoBlast treatment.



Figure 5: Knoop micro-hardness values for the three metal alloy substrates

3.2 Coating Thickness

The thickness of the CoBlast deposited HA coatings on each of the metal alloy substrates were obtained based on cross sectionals examination (Figure 6), combined with the use of Digimizer software. Considerable variation in coating thickness was observed due to the roughness of the blasted metal alloys, the thickness values obtained are based on an average of 64 measurements on each coating. The HA coatings deposited onto the titanium substrates were found to have an average coating thickness of $3.0 \,\mu$ m, compared to the 2.0 and $2.3 \,\mu$ m coatings deposited on the cobalt chrome and stainless steel substrates (Figure 7). It is important to note, that while the CoBlast deposited HA coating thickness varies across the metal substrate surface, based on optical microscopy examination, there was no evidence of uncoated areas.



Figure 6: Typical SEM cross sectional micrographs of the HA coatings on the three substrates (Scale Bar = $10 \mu m$)



Figure 7: Variation in HA coating thickness obtained on the three substrate surfaces determined using the

Digimizer software

The increased HA thickness observed on the Ti substrates may be associated with its enhanced reactivity to oxidation, due to the greater variance in 'Pauling Electronegativity' between titanium and both oxygen and hydrogen 35 . This enhanced reactivity may in turn facilitate a higher level of bonding to the oxygen and hydroxyl functional groups within the HA molecules 35 . It has been reported previously that the adhesion of the CoBlast deposited HA coating may be a combination of mechanical interlocking and 'mechano-chemical bonding', which is a type of chemical bonding brought about by specific mechanical interactions 36,37 . This type of functional bonding would

support the suggestion that Pauling Electronegativity is a contributing factor in the bonding process 25,35-38

3.3 Coating adhesion

As detailed in Figure 8 the scratch test results for the CoBlast deposited HA coatings, show broadly similar coating failure loads independent of the substrate metal alloy, with average values ranging from 52 to 63 N. In contrast to the coating delamination failure mechanism often observed for PVD coatings, no significant delamination was observed to the coating around the scratch. The failure points of the coatings were confirmed using EDX, which showed a significant drop in the presence of Ca and P (constituent elements in HA), at the base of the scratch's. The results suggest the adhesion of the CoBlast deposited HA coating is independent of the substrate metal alloy. The marginally higher level in the mean coating failure load for the HA coatings deposited on the titanium alloy substrate may be associated with the titanium's enhanced reactivity to oxidation, as discussed previously ^{25,35,38}.



Figure 8: Scratch adhesion test results for the CoBlast HA coatings on each of the substrate types as shown

3.4 APS Coatings

Having provided details on the APS coating morphology, thickness and adhesion on the CoBlast deposited HA coatings, this section provides information on the APS deposited HA coatings on the same substrates ²⁹. Evaluation of the APS HA coating thickness (Figure 9) found that each of their thickness values fell within the optimum thickness range of between 50 and 70 μ m, which is reported to help avoid fatigue failure and embrittlement of the coating $\frac{16,39-41}{2}$. It was also apparent from Figure 9 that each of the APS deposited coatings have similar thickness values irrespective of the substrate materials utilised in their deposition. Indicating the coating property, coating thickness, is independent of the substrate material. This independence of the substrate material is attributed the APS technology's high process temperature (approx. 6000 K), allowing most ceramic materials to be heated to a molten form and deposited onto most substrate surface capable of withstanding the process's thermal properties. This reflects the difference between the CoBlast and APS technologies, where the former's coating properties are influenced by the substrate material properties as detailed in this paper amongst. As previously highlighted however, there are concerns regarding the affect this high processing temperature has on the properties of the APS deposited HA coating $\frac{1,5,11-16}{1}$. The composition of both the HA coatings and the substrate beneath were assessed using EDX and XRD, and a comparison was drawn between the CoBlast and APS treated samples.



Figure 9: APS HA coating thickness obtained on the three substrate surfaces determined using the Digimizer software

3.5 Compositional Analysis of the CoBlast and APS Deposited Coatings

Energy-dispersive X-ray spectroscopy (EDX) analysis was performed on each of the CoBlast deposited HA coatings to determine if the deposition process affected the composition of the HA materials. The results of the EDX elemental analysis are shown in Table 2. These results show that for each of the CoBlast deposition HA coatings, the EDX technique detected elements present in the substrate through the coating. This is due to the EDX X-ray penetration depth of up to 4 μ m (system operated at 15 kV fixed acceleration voltage), which is greater than the thickness of the CoBlast deposited HA coatings (see Figure 7) ²⁵. Based on the EDX analysis, an average weight percent ratio of 2.2 for calcium to phosphorous (Ca/P) was obtained for the CoBlast coatings, this is close to the ratio of 2.1 for the precursor HA powder. In contrast, EDX evaluation of the APS coatings found an average Ca/P ratio of 2.9 for the HA coatings on all three substrates, suggesting similar levels of chemical alterations had occurred on each of the substrates during the APS deposition process.

Material	Calcium (Wt%)	Phosphorous (Wt%)	Substrate (Wt%)
CoBlast (CoCr)	47.7	22.6	29.7
CoBlast (Ti)	48.8	21.1	30.3
CoBlast (SS)	49.1	22.0	28.9
APS (All substrates)	74.3	25.8	-
Powder	67.3	32.7	-

 Table 2: EDX results obtained for the CoBlast and APS HA coatings deposited on each of the metal alloy substrates

An X-Ray Diffraction (XRD) study was carried out on each of the HA coatings and treated substrates alloys after etching of the HA coating. As demonstrated by the XRD spectra given in Figure 10, the CoBlast deposited HA coatings on the three substrate alloys exhibit a crystalline structure similar to that of the precursor HA powder (as is supported by the EDX results). Their peak positions and intensities match those of the precursor HA powder spectrum. This was quantified and verified using MAUD analysis software ³⁰⁻³³, demonstrating that the low temperature deposition process of the CoBlast technique allows the crystallinity of the precursor HA powder to be retained regardless of the substrate alloy. Prevéy reported the XRD peak broadening, displayed in each of the HA coating spectra, may be due to the existence of nanocrystalline HA ⁴².

XRD of the APS HA coatings were compared with those obtained using the CoBlast process. While the APS coating exhibit's similar peaks to the precursor HA powder, the MAUD analysis software estimates greater than 9 wt. % of the HA coating has been converted to alternative calcium phosphate phases, such as; tri-calcium phosphate (TCP), tetra-calcium phosphate (TTCP). The presence of the 'amorphous halo' (highlighted in Figure 10), associated with amorphous HA, indicates further deviation from the precursor HA powder has occurred during processing ^{1,43-46}. The amorphous content in the coating was however not quantifiable using the MAUD software due to inherent limitation in the software ^{30-33,44}. It should be noted that calcium phosphate phases such as; TCP, TTCP and amorphous HA, are known for their increased dissolution rates, which has been reported to allow for rapid osseointegration, when compared with the pure HA. These phases however, are generally associated with rapid bone formations $\frac{1}{2}$, rather than stable, lamellar bone observed previously for CoBlast coatings $\frac{25}{2}$. Significantly, the XRD spectra for the APS processed titanium and stainless steel substrates mirrored that of the cobalt chrome spectrum shown in Figure 10, verifying that thermal modification of the HA powder occurs irrespective of the substrate alloy type $\frac{1}{2}$.



Figure 10: The XRD spectra of the HA powder and CoBlast deposited HA coatings on the three substrate alloys The substrate spectra in Figure 11 relate to the XRD evaluation of the alloy substrates onto which the deposited HA coatings have been applied. The evaluation of the substrates was facilitated by removal of the HA coating via acid etching as detailed earlier. From Figure 11, it is clear that the CoBlast processed substrates experience no significant change in crystal structure, as their peak positions and intensities match those of the 'Bare' unprocessed substrates. This was verified by MAUD analysis, where the 'Bare' and CoBlast processed substrates were found to have similar weight percentages of substrate associated phases present. This again demonstrates the minimally invasive nature of the low temperature CoBlast deposition process with respect to the metal substrate phase composition. In

contrast, MAUD analysis of the APS processed substrates established that phase alterations were exhibited in both the titanium and the chrome substrates. In the case of the latter, for example, peaks located at 47.1° and 51° were no longer identified in the metal alloy substrate spectra after the APS HA processing. The changes which occur in the titanium and cobalt chrome have been shown previously to be associated with high deposition temperatures, and have been suggested to significantly alter the mechanical performance of the metal alloys ⁴⁷. Stainless steel however, was unaffected by APS processing. This was attributed to the high transus temperature (temperature where phase transition initiates) of the stainless steel alloy (<1050 °C) relative to titanium (<880 °C) and cobalt chrome (<890 °C) alloys ⁴⁸. Below this transus temperate, the stainless steel alloy would maintain its phase composition including, its FCC structure, while phase changes would have initiated in the titanium and cobalt chrome alloy substrates almost 200 °C below the temperature at which this occurs for the stainless steel substrates ⁴⁸.

Significantly, there are 5 distinct peaks which occur in the APS processed samples (asterisks * in Figure 11), which are not present in either the uncoated or CoBlast processed substrates (with the exception of one overlapping peak in the titanium alloy spectrum). It was determined these peak represent the presence of Al_2O_3 contaminant, typically utilised in the pre-processing stages of the APS process ⁴⁹. This was verified by MAUD analysis, indicating that Al_2O_3 could account for as much as 22 wt% of phases present at the HA/substrate interface, cross sectional SEM and spot EDX was also employed to confirm the presence of this material. Figure 12 shows a cross sectional micrograph, where an embedded Al_2O_3 particles is evident and the result of the spot EDX evaluation is given. This was also observed by Garcia-Sanz et. al. ⁵⁰. It is interesting to note that despite Al_2O_3 powder being used as an abrasive for the CoBlast process, no significant levels of Al_2O_3 was detected in the deposited HA coatings, as highlighted previously ^{25,38,51}. The XRD findings are in agreement with previous work carried out on titanium grade 5 substrates with APS deposited HA coatings, where similar levels of both HA and substrate phase alterations were observed.



Figure 11: XRD spectra for the three substrates after HA removal. The peaks indicated by * were neither observed in the bare substrate or the HA coatings



Figure 12: SEM cross section of an APS deposited HA coating exhibiting an Al₂O₃ particle embedded in the titanium alloy substrate beneath the coating, Spot EDX data of the cross-hairs location is given also

4 Conclusions

In this study the influence of substrate alloy type (cobalt chrome, titanium grade 5 and stainless steel) was investigated with respect to its effect on the properties of HA coatings deposited using the CoBlast technique. The HA coated alloys were found to present similar interfacial properties and coating composition irrespective of alloy type, however, surface roughness and coating thickness were observed to vary between the three substrate types. The trend of increased roughness of cobalt chrome > titanium > stainless steel, appears to correlate with the micro-hardness of the alloys, with higher micro-hardness it is likely that the alloy will exhibit higher resistance to particle abrasion on the micro-scale. The variation in coating thickness may be associated with the Electronegativity of the different metal alloys examined, were a greater difference in Pauling Electronegativity to oxygen could explain the higher level of reactivity with the HA. The crystallinity of the CoBlast deposited coatings were observed to matched those of the precursor HA powder, demonstrating that the CoBlast deposition process did not affect the crystal structure of the HA, in addition, it was also observed not to affect the substrate's crystal structure. Conversely, the XRD analysis showed that the titanium and cobalt chromium substrates were altered by the high temperature APS technique, and furthermore the deposited HA was modified when compared to that of the precursor HA powder. The advantage of the CoBlast process therefore is the minimal alteration observed for both the HA coating and substrate alloys, with a further advantage being the absence of significant levels of Al₂O₃ in the CoBlast processed substrates. In contrast Al₂O₃ is presented in the APS deposited coating due to the abrasive pre-treatment used, which if not managed correctly could lead to third body wear of a device during implantation. In conclusion, this investigation demonstrates the suitability of the CoBlast technique in successfully deposit HA coating onto stainless steel and cobalt chrome alloys used routinely in the orthopaedic industry, in addition to the titanium grade 5 substrates previously investigated.

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