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Review paper

Consequences of hydroxyapatite doping using plasma spray to implant biomaterials

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Abstract

Hydroxyapatite (HAp) is still one of the most common bioactive coatings used on metal implants in orthopaedics due to its biocompatibility. The application of HAp to metallic implants can be accomplished using a variety of processes. Plasma spray (PS) coating stands out as the method of choice due to its dependability, affordability, and ability to protect metal surfaces against rust and wear. The use of HAp in medicine has been limited due to the material's unfavorable mechanical characteristics, such as brittleness, a lack of fracture toughness, and inadequate tensile strength. In addition, the remodeling durations of HAp-covered implants are significantly longer, the rate of osseointegration is significantly lower, and no antimicrobial actions or features are present in these implants. The mechanical and biological properties of HAp have been improved by applying various approaches, all of which fall under the category of surface modification tactics. Dopants are one of those strategies that are extremely successful at changing the characteristics and using them in HAp is one of those methods. As a result, this review study aims to consolidate data on implant Hap coating using the plasma spray approach and assess the benefits and problems associated with employing this method. In addition, the paper addresses how altering the structural, chemical, and mechanical features of HAp can assist in overcoming these limitations. In conclusion, it explains how the incorporation of entering the HAp structure can change the features that, when coated using the plasma spraying approach, alter the functionality of the implant.

Keywords

Natural bone; strong bonding; orthopaedic fields; bioactive coating

Introduction

Fractures of the bone are a common complication of bone-related diseases in individuals worldwide, which often necessitates bone transplantation. In addition, the world population increases. As a result, the contention that there is a growing demand for prosthetic implants to treat bone-related difficulties is well-founded. The implants are frequently utilized in orthopaedic and maxillofacial reconstructive procedures. As a result of the growing demand for the implants described above, there is also a requirement for the development of novel implants that are exceptionally biocompatible and feature a high level of functionality [1-3]. Metallic materials are the most common choice for implant construction because of the exceptional mechanical properties they possess for the hard tissues found in the human body. Metallic implants, on the other hand, provide a challenge of biocompatibility. Metallic implants also have a number of drawbacks, including a high rate of corrosion, a deficiency in anti-infection properties, and a tendency to become loose due to the creation of potentially harmful wear debris particles. As a result, one of the most significant problems associated with metallic implants is an early failure. Thus, it is essential for the implant's continued viability to improve its features while simultaneously decreasing its negative sides. One strategy for improving the characteristics of implants and extending their lives is to cover them in bioactive material [4-6]. The hydroxyapatite (HAp) material that is coated on biomedical implants is by far the superior choice when compared to the other bioactive materials that are used. It has a significant versatility in clinical settings throughout the orthopaedics areas. The fact that calcium (Ca)/phosphorrous (P) molar ratio is both physically and chemically comparable to that of natural bones is the primary advantage of this material. In addition, implants with a HAp covering have excellent biocompatibility, conductivity, quicker implant attachment, and a strong relationship with living bone [7].

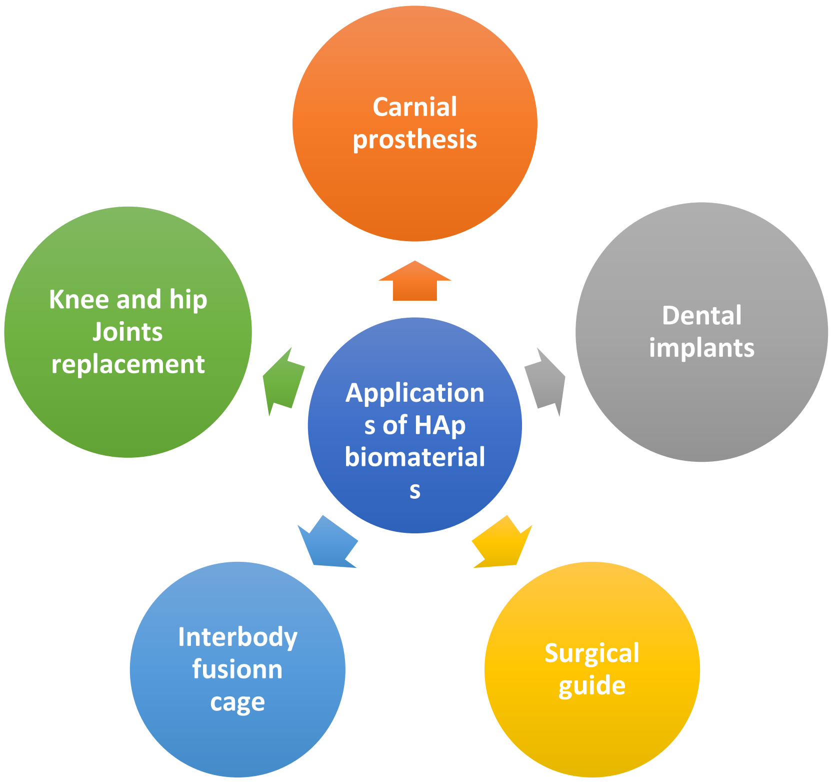

Figure 1. *Various potential uses for HAp biomaterials*

As in Figure 1, HAp is frequently used as a covering material for implants. This is done so that artificial cement-free bone can be replaced in implants. Metallic implants with excellent biocompatibility and bioactivity also have good strength and high ductility after being coated with HAp. This is because HAp has a high molecular weight. The use of HAp as a material for covering metallic implants can be accomplished using a wide variety of processes, such as plasma spraying, oxy-fuel high-velocity combustion spraying, dip coating, ion-beam sputter coating, and electrophoretic deposition. Ca-P coatings with better adhesion have been employed recently, primarily on magnesium-based alloys. These coatings were primarily inspired by organic molecules. The plasma spray coating process is one of the many available options, and it stands out thanks to its benefits over other approaches. For example, the electrophoretic deposition technique can only be used for the deposition of immaterial substances. The high-velocity process for oxy-fuel is limited because of the high cost of the necessary equipment, the restricted powder size, installation requirements, and application complexity. In a manner analogous to this, ion-beam sputter coating is limited in its capabilities due to the limited size of the ion beam, slow deposit, and restricted bombardment target [8-10].

In most cases, thin and thick coatings are placed on bioimplants in order to protect them from corrosion and erosion [11-14]. Both corrosion and erosion have a significant negative impact on the longevity and tenacity of the various materials [15-30]. Various surface protection techniques are used commercially, such as claddings [31-43], electrochemical vapor deposition (EVD) [44], chemical vapor deposition (CVD) [45-48], plasma vacuum deposition (PVD) [13,42,49-54], HVOF/HVAF [17,18,25,28-30,55-63], plasma spray (PS) [64-66], sputtering [13,60,67-74], dip coatings [46,67,75-79] *etc*. When it comes to biomedical applications, thin coatings are often favoured over thick coatings. Thick coatings might be problematic [72,74]. The use of a dip coating can be problematic due to inadequate mechanical qualities such as adhesive strength. The benefits and drawbacks of utilizing these tactics have been elaborated upon elsewhere [79]. When everything is taken into consideration, the plasma spray coating stands out as the most dependable and most dependable practical, low-cost method of shielding metal from wear and corrosion. In addition to these benefits, it has a smaller porosity, a surface free of fractures, improved mechanical properties, and minimal contaminants. In addition, it increased biocompatibility, which led to a quicker bone-implant attachment and better adhesion between them. This was made possible by the chemical and structural similarity between metal implants and bone minerals, as well as the implants' superior surface quality. Consequently, the method of plasma spraying is commonly used to cover the surface of orthopaedic implants, and it is also feasible from a business perspective. This was made possible by the chemical and structural similarity between metal implants and bone minerals, as well as the implants' superior surface quality. The use of HAp as an implant covering is limited due to the material's unfavorable mechanical characteristics, such as brittleness and a lack of fracture toughness. Despite the fact that HAp is an excellent material to use, its application in medicine is restricted. In addition, the remodeling time for HAp-coated implants is longer, the rate of osseointegration is lower, and there are no antimicrobial actions or features present in these implants [80-82]. Because of these and other constraints, HAp-coated implants' biomechanical properties need to be altered before they can be used for long-term applications. It is imperative that the HAp material's phase, morphological, structural, and compositional features be accurately regulated to further enhance the osteoblast cells' bio-functionality when they are used as a coating material on the surface of the implant. This is a result of the fact that the surface features of the material can have a significant influence on the way in which the cell and the coating layer interact with one another. Numerous strategies have been implemented as surface modification techniques in the quest to enhance the HAp's mechanical and biological properties. Doping ions into the HAp is one of these approaches, and it is one of the more successful methods for modifying the properties of the HAp. This review paper will assemble essential material in order to analyze the benefits and downsides of biomedical implants with the HAp (PS) method. Specifically, this paper will focus on biomedical implants [83-85]. Overcoming limitations by altering the structural, chemical, and mechanical properties of HAp is also discussed. In the end, it explains how the incorporation of doping single, binary and multi-ion HAp has the potential to change the properties that, after being coated by plasma spraying, alter the functionality of the implant.

Hydroxyapatite plasma spray coating

As a result of its many benefits, plasma-spray-coated HAp on metallic implants has found broad application in orthopaedics and dentistry. Using a plasma flame generated by an electrical discharge between electrodes, the plasma spraying approach's primary goal is to elevate HAp particles' temperature to very high levels. Soon after being deposited, the molten HAp particles cool rapidly to create a coating layer on the surface of the substrate. After the coating cools, it has been shown that partial apatite breakdown occurs, which may be easily characterised by the thermal stability of apatite, and other secondary phases formation. In the vast majority of instances, this has been the case. The use of HAp plasma spray coating on metallic biomedical implants has been the subject of extensive research. Coatings of HAp and tetra calcium phosphate (TCP) were sprayed onto a titanium substrate using a plasma spraying technique for biomedical applications, and it was found that plasma-sprayed composite coatings with tunable solubility can be obtained for the orthopaedic and dental applications by selecting a specific powder composition and then undergoing a subsequent thermal treatment [86,87]. This was discovered through the application of the method for biomedical use. When they applied a PS coating of simply HAp and 80Al_2O_3-20TiO_2 to a Ti6Al4V substrate improved reinforcing the most advantageous characteristics of a coating. This was discovered when they found that the coating could be advantageous for the implants. Because of the reinforcement, it was also discovered that undesired phases such as tetra calcium phosphate (TTCP) and tri-calcium phosphate were present. These phases could be harmful because of their quick breakdown in the environment of the body; thus, their presence was noted. The outcome of applying HAp and HAp-silicon oxide coatings deposited by using plasma spraying on the stainless steel is significant in biomedical applications. Their research showed that the HAp-coated substrate had a lower corrosion resistance than the composite coating but a higher resistance than the untreated substrate [88,89]. According to reports, the porous structure of the HAp coating makes the corrosion worse. The plasma-sprayed HAp and HAp-Ti composite coatings on Ti6Al4V substrate were demonstrated to have bioactive qualities when subjected to an eight-week immersion in a simulated bodily fluid (SBF) solution. They came to the conclusion that the layer had been through two unique stages: first, it had undergone a process of disintegration, and then, on top of that, an apatite crystal precipitate similar to the bone had evolved. In addition, they found that the coating's mechanical strength decreased as the soaking time rose, owing to the coating's propensity to become detached from the substrate as a result of a lack of adhesive strength in the coating. They claimed that composite coatings performed better in terms of mechanical strength than pure HAp coatings, indicating enhanced long-term stability in a physiological environment [90,91]. Their reasoning can be found here. In order to improve the PS HAp bonding strength, it is necessary to first make a composite out of titanium and then coat it on the surface of substrates made of titanium alloy. They stated that including Ti in the coating resulted in a considerable improvement in the coating's bonding strength while preserving the bioactivity of the HAp coating. To look into the mechanical and microstructural properties of coatings made of HAp, YSZ, and Ti6Al4V that were sprayed using a plasma, they claimed that in comparison to PS coated HAp, where TCP and CaO phases were present in trace amounts, but other phases such as TCP and TTCP were absent, composite coating demonstrated superior levels of mechanical strength. The melting of particles, the rate at which they cooled, recrystallization, re-hydroxylation, dehydroxylation, and the efficiency with which they deposited material during plasma spraying were all related to phase and structural changes, as indicated by studies. According to studies that investigated the connection between spraying parameters, the rate of dissolution, and the surface attributes of HAp coatings.

Increasing the PS power distance led to a gradual deterioration in the phase purity and crystallinity of HAp. Coatings sprayed at higher intensities and for longer distances showed significantly more particle melting, the researchers found. The surfaces of the coatings exhibited this behavior [92-94]. Coatings sprayed with less force were also found to have a crystalline HAp structure. Coatings sprayed at higher intensity, however, displayed a pattern reminiscent of bone apatite. This was the case regardless of the type of coating. Researchers have hypothesized that plasma spraying may be used to produce HAp coatings that are dense, adhesive, and bioactive.

Restriction to HAp coating

In order to stimulate bone formation and speed up the healing process, HAp is a popular implant coating. The use of polysulfone HAp-coated biomedical implants attracted a lot of interest and controversy during the past few years. Even though reports have suggested that HAp-coated implants attach more rapidly and thoroughly and promote greater bone development, the longevity of these implants is still in question. This chaotic behavior is brought on as a result of the thermal disintegration of HAp that occurs during the plasma spraying process. This process tends to bring to light a variety of observable downsides regarding the coating's chemical, physical, and biological properties [95-97]. Numerous investigations have been conducted on the possibility of utilizing HAp-coated metal implants to reconstruct human bone pieces that have been lost or shattered. However, due to weak resistance to wear and corrosion, the implants that are now in use have been shown to deteriorate over the course of several years. The presence of porosity in a physiological environment has a detrimental effect on the corrosion resistance of HAp-coated implants. This is the case even when the porosity is quite small. It has been reported that the plasma spraying method causes HAp to degrade, which results in the formation of phases such as calcium oxide, tri-calcium phosphate (TCP), tetra-calcium phosphate (TTCP), and others. The dissolution creates a poor coating-metal connection, the discharge of particles, and delamination as a result of the loss of cohesive strength [97-99]. The HAp coating utilized in medical applications slows the process of osseointegration. However, it does not possess any antibacterial actions or features. To make HAp practical for use, its mechanical strength and bioactivity must be enhanced. The potential is limited because it has a low mechanical interfacial strength and takes a relatively long period to reconstruct.

Implications of doping to overcome constraints

The performance of HAp coating is affected by its components, including its composition and structure, as well as its physical, biological and mechanical properties, which prevent synthetic HAp from being used as an implant for artificial bone in load-bearing orthopaedic applications. These characteristics limit the implantation of synthetic HAp. As a result, it is absolutely necessary to enhance these properties for implants to be used for a wide variety of load-bearing applications for an extended time. Several approaches have been utilized to achieve this level of excellence. The development of ion-doped changed HAp is one way that can be utilized. Recent research has focused a lot of attention on ions because their substantial contribution to the production of artificial bone with superior bioactivity and mechanical characteristics has garnered a lot of recent attention. In addition to calcium and phosphorus, it is general knowledge that hard tissues such as bone, enamel, and dentin contain a great deal of other trace elements as well [99-101]. Other structural similarities between bone and ion-doped apatite that served as an inspiration for the development of this material are also present. It is possible to incorporate either cationic or anionic substituents into a HAp structure. Substituted hydroxyapatite (SHA) has a reduced solubility in a physiological environment due to the effects of these dopants on HAp's morphology, crystallinity, and lattice properties. In other words, this is due to the existence of these dopants. A safer and more effective method of enhancing the coating's tissue ingrowths and angiogenesis properties can be provided by integrating dopant ions into the HAp structure. It was found that the biological reaction to natural HAp with a non-stoichiometric structure is greater than that to stoichiometric HAp. The presence of extra ions and a lower Ca/P (1.5) molar ratio in natural HAp led researchers to this conclusion [102,103]. It has been proven in both *in vitro* and in vivo experiments that doping with ions boosts material's mechanical characteristics and accelerates bone formation and resorption. The initial rate of degradation, the mineralization property, and, most importantly, the biological activity of HAp are all affected by the introduction of dopants due to the wide range of crystal defects and changes in surface charge introduced throughout the doping process.

Effects of single ion doped HAp

As shown in Figure 2, single ionic doping can change the parameters of the HAp structure. These changes are dependent on the quantity and length of the dopant. As a direct consequence of this, a great number of research projects focusing on the production of single ion-doped HAp have been carried out. When it came to the synthesis and subsequent structural characterization, it was determined that single ion doping in the HAp structure was the simplest option [104,105]. As a coating material for biomedical implants, we will explore the effects of single ion doping on HAp structure in the following sections. Particular attention will be paid to coatings applied using plasma spraying when this method is most applicable.

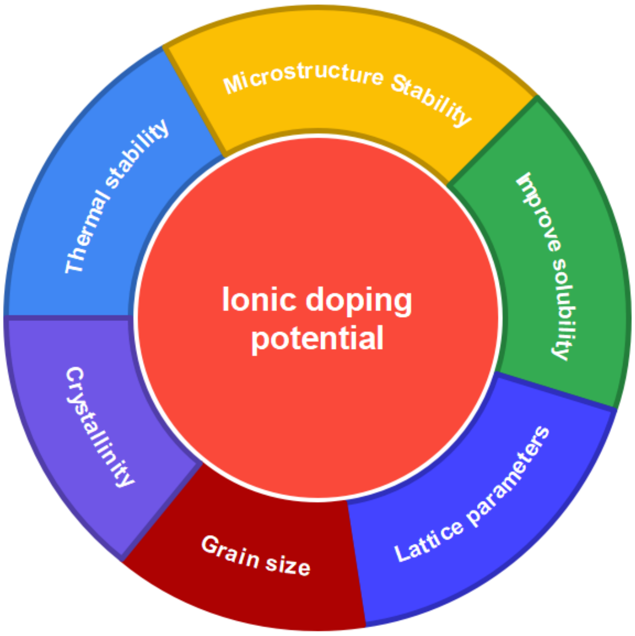

Figure 2. *Ionic doping potential*

HAp doped with Sr

It was found that strontium, one of the many different types of metallic dopant ions, was especially useful in improving synthetic HAp's biological and structural properties. It is beneficial on the treatment of osteoporosis and is most commonly found in regions with high metabolic activity. In these regions, Sr can be found in the bone mineral phase. *In vitro* studies show that it increases the number of osteoblast cells while simultaneously decreasing the activity of osteoclasts. In addition, it has been found that Sr can reduce the amount of bone resorption that occurs while simultaneously increasing the number of preosteoblastic cells that multiply, encouraging osteogenesis, osteoblast differentiation, and the development of new bone. When utilized as a dopant to HAp, the ion with the charge of Sr^{2+} can replace or substitute Ca^{2+} ion for the whole composition range. To fully realize the effect of Sr on the HAp structure during PS deposition, numerous studies have been conducted to investigate the effect that different Sr doping concentrations have on the structure of HAp [106,107] The level of cell adhesion increased with the strontium content. Sr doping was shown to gradually decrease the crystallinity. Prodan *et al.* [108] used to create Sr doped HAp powder with 15 mol.% Sr and reported the decreased crystallinity with a concentration more than 2 mol.% of Sr. In addition, it was observed that the TCP phase was present in the latter. Further, it has been found that higher Sr concentrations contributed to the stabilization of the HAp phase with the removal TCP phase. The higher Sr concentration, which was above 15 weight percent, led to the destabilization of the HAp structure, which resulted in the formation of TCP as a secondary phase. They came to the conclusion that single-phase HAp could include as much as 1.5 % strontium. The inclusion of these other phases causes apatite to become destabilized, which leads to a loss in crystallinity and crystallite size. The decrease in crystallinity and crystallite size may be induced by an increased quantity of strontium incorporation. Because of the low strontium content, both the crystallinity and the crystallite size of HAp were found to be diminished, whereas an increase in strontium concentration was discovered to cause an increase in both of these features. When strontium-doped HAp was implanted into bone fractures, the procedure encouraged the formation of new bone, indicating that osseointegration had been successful. During the in *vitro study*, the used cells derived from a fetal osteoblast cell line known as hFOB. They found that Sr-HAp-coated surfaces had superior initial cell adhesion and greater cell proliferation compared to HAp-coated surfaces. One possible explanation is the effect strontium has on the rate of early differentiation as well as the activity of ALP [109,110]. They concluded that the incorporation of Sr into Hap resulted in a significant enhancement of the material.

Recent studies have demonstrated that strontium affects the mineral metabolism that occurs during bone regeneration. Specifically, strontium promotes the formation and proliferation of osteoblasts while suppressing the activity of osteoclasts in the case of strontium-doped HAp coating. Because Sr-HAp is significantly more bioactive and has improved solubility compared to HAp, its application in vivo is necessary. The results of all of these tests point to the same conclusion: Sr incorporation fosters cell adhesion and cell growth. In addition, the study found that doping the coating with strontium increased its bioactivity without diminishing its mechanical properties, making it an excellent candidate for implant coating.

Mg-infused HAp

Magnesium (Mg), the fourth most prevalent trace element in mammalian bodies, is essential for the catalytic activity of over one hundred different enzymes. It is a large trace ion found in bones and teeth. It does this by quickening the activity of osteoblasts, particularly in the early phases of osteogenesis, which speeds up bone metabolism. A deficiency in magnesium ions can cause problems with bone formation and metabolism, a loss of bone density, and an inhibition of osteoblast activity, all of which contribute to an increased risk of bone fracture [111,112]. Since HAp with magnesium doping has the potential to be used in a variety of biomedical applications, a significant amount of study has been conducted on the topic. To explore the effect of different concentrations of the Mg2+ ion on the Mg-HAp coating applied to the Ti alloy substrate. They discovered that it had a greater level of biocompatibility when the magnesium concentration reached 2 percent by weight. However, because the coating has a greater specific surface area and smaller crystallite size, it is better adapted to receive proteins or drugs that induce bone formation. This is because the coating has a higher specific surface area. When compared to stoichiometric HAp granules that are commercially available, it has been observed that osteoconductivity and solubility are improved when Mg-doped granules are implanted in rabbit femoral bone defects [113,114]. Despite the beneficial effects that the Mg-doped HAp coating by PS method on biomedical implants has, there are not many writers working on it.

Zn-modified HAp

Zinc (Zn), a trace metal found in bone minerals, plays a critical role in the regulation of the immune system and the development of bone. In addition, it can stimulate the metabolism of nucleic acids, bone growth, cell division, enzyme activities, the maintenance of membrane structures, and, most importantly, the calcification of diseased conditions. It can prevent bone loss and the absorption of bone by osteoclasts in vivo. It also has the potential to improve bone formation and metabolism in addition to its corrosion resistance activities. When more than 10 weight percent of zinc is doped into HAp, an increase in the amorphous apatite phase occurs. By introducing Zn into the structure, grain size can be decreased while at the same time increasing HAp's solubility [115,116]. It is possible to replace Ca with Zn at a concentration of 20 mol% so that the cation can penetrate the apatite lattice rather than remain on the surface. Zn can increase the formation of new bone and a reduction in bone resorption by decreasing osteoclastic activity. A Zn-doped HAp coating was applied to the Ti rods, and an effective rise in fibroblast cell proliferation was found after its application. In addition, a number of experiments have demonstrated that increasing the amount of zinc in HAp increases the material's mechanical properties [117]. In addition, HAp possesses antibacterial and anti-inflammatory qualities, all of which lend credence to the idea that it could be utilized as a material for bone restoration cell differentiation and adherence on surfaces treated with Zn-doped HAp. The research demonstrated that doping HAp led to increased bone protein gene expression and greater levels of both ALP and osteogenic activity. The rabbit tibia model was used to carry out in vivo testing. They discovered that Zn-doped HAp had significantly improved biocompatibility as well as osteoconductivity [118]. Numerous studies revealing better HAp osseointegration and physiologic responses have been published on plasma spray Zn-doped HAp coatings. As a result, a wide variety of opportunities for applications in biomedicine are available. However, the powder is subjected to high temperatures throughout the process [119,120]. However, up to now, the applications of Zn-doped HAp, such as its optoelectrical properties, anti-cancerous activity, and ability to operate as a corrosion-resistant coating, have not being utilized to their full potential.

Effects of binary doped HAp

This section describes the physical, mechanical, biological, cytotoxic, and antibacterial properties of the coated binary-doped HAp Doping with binary or multiple ions can affect various physical properties, such as the phase, crystallinity, mechanical properties, and lattice parameters of a material [121]. After being coated in doped HAp, the physical features of biomedical implants, such as phase and surface porosity, change [122]. This is because the plasma temperature, interactions with the substrate and spraying circumstances all play a role in this transformation.

Doping results on electrochemical and mechanical properties

It is not possible to employ dense pure HAp as a replacement for hard tissue due to the material's inadequate mechanical strength, which includes inadequate fracture toughness and bending strength. Since its mechanical properties can be enhanced by adding dopants, HAp is often treated with them. Coatings of HAp were strengthened using a wide variety of materials, including SiO_2, CaP, ZnO, and Sr, to enhance bio-implant corrosion resistance and mechanical properties. This was done to meet regulatory requirements. The implants' corrosion resistance and biodegradability are also improved [123,124]. ZnO is added to HAp to improve its corrosion resistance and mechanical properties for use in bio-implants. These properties include surface hardness, surface roughness, and surface wettability. It is a novel inorganic substance with a wide range of applications and a consistent set of chemical and physical properties. It plays an essential part in the maturation of bone as well as the increase of a material's resistance to corrosion. A limited amount of research is being conducted on Ti13Nb13Zr alloys with a plasma-sprayed HAp/ZnO reinforced coating for potential use in the biomedical industry [125-127]. In light of this, the surface features of the Ti13Nb13Zr alloy and the electrochemical corrosion behavior was investigated. The E_{corr} of coated samples was significantly higher compared to the E_{corr} of naked titanium alloy samples. The coated samples appear to be less corrosive and exhibit a continual increase in the amount of ZnO in HAp. As a result of increased resistance to corrosion, a more robust attachment between the implant and the tissue develops [128]. It has the additional effect of causing the damaged tissue to heal rapidly and in a short amount of time. Electrochemical experiment revealed that the Ti13Nb13Zr alloy was better protected against corrosion by HAp/ZnO-reinforced coatings than by pure HAp coatings. This was the case regardless of the kind of coating used. The I_{Corr} value declined even more when reinforcement in the form of ZnO was added to the HAp, and the sample coated with (HAp+12 % ZnO) had the smallest I_{corr} value [129,130].

In prior experiments, specimens with HAp/ZnO coatings displayed substantially stronger corrosion resistance than the naked alloy. It has been hypothesized that the ions that are generated due to the corrosion of metallic implants may affect cell metabolism. The difference in surface roughness between coatings made of pure HAp and coatings made of HAp reinforced with ZnO may have been a factor in the reduction in Icorr value, which indicates an improvement in corrosion resistance [131]. The degree of roughness of a surface has a substantial impact on the corrosive behavior. When compared to a surface with a finer texture, a surface with a coarser texture is more likely to develop pits. With implants manufactured of Ti13Nb13Zr better corrosion resistance was achieved, hence preserving their mechanical strength [132,133]. The current research demonstrated that ZnO reinforcement boosted the ability of the HAp coating to withstand corrosion, which would boost long-term survival and osseointegration. On the other hand, surface hardness is an essential mechanical property frequently linked to the rate of surface deterioration in implants. This association exists because surface hardness is a measure of how well an implant resists wear. The microhardness of a surface also has a substantial impact on the material's ability to resist corrosion.

Conclusion and prospective future

A significant amount of research has been done on plasma spray (PS) coating of HAp on metallic implants because of Hap's outstanding bioactivity in physiological environments. The current study findings lead to the following deductions:

1. The plasma spraying leads to the formation of TCP phase in the developed coating surface. The apatite formation is slow in such cases due to the presence of unwanted phases present on the surface.

2. The reduction in the undesired phase formation can be achieved by using dopants, which increases the crystallinity of the coating with the optimum concentration.
3. The other techniques such as HVOF and cold spray has limitations such as high cost of the tools required, the limited powder size, the realising, and the product complexities in the development of bio-implant HAp -based coatings.
4. HAp coatings were reinforced with a range of materials, including SiO_2, CaP, ZnO, and Sr. This was done to improve the corrosion resistance and mechanical properties of bio-implant applications.
5. When implants were comprised of titanium-based alloys, such as Ti13Nb13Zr, their enhanced corrosion resistance protects the implants from corroding as fast, sustaining their mechanical strength.
6. The activity of bone resorption was examined in the presence of a strontium-doped HAp coating. As a result, it is an appropriate choice for use as an implant coating. Mg-doped HAp granules are better suited to receive proteins or medications that stimulate bone growth.
7. The ZnO reinforcement can enhance the HAp coating's ability to withstand corrosion, which improves long-term survivability and osseointegration.

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