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An Overview of Biomedical Materials and Techniques for Better Functional Performance, Life, Sustainability and Biocompatibility of Orthopedic Implants

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Abstract

Objectives: Improvement in the functional performance and biocompatibility of biomedical implants using different bioactive materials and coating techniques. **Methods/Statistical Analysis**: The requirement of bio activity, biocompatibility with proficient mechanical properties without immune rejection for long lasting implants and bone substitutes is a tremendous challenge. These bone substitute structures ought to be set up for individual patients with all details controlled on the micrometer level. **Findings:** The metallic implants (Ti-alloys, Co-alloy and Stainless steel) utilized by researchers to investigate bone fractures and imperfections are unsuccessful to perform in biomedical applications as they failed to build required bond with living bone. The scientists proposed combining the bio activity of bioactive materials and excellent mechanical properties of metals by depositing bio active materials on metal base material. **Application/Improvements:** Many methods like plasma spraying, thermal spraying, pulsed laser ablation, sputter coating, etc., were utilized to efficiently coat bioactive materials on metal base. In this paper, we will review the bioactive materials including different methods utilized in depositing bio-ceramics and effect of cryogenic processing on biomedical implants.

Keywords: Biomedical Materials, Coating Techniques, Cryogenic Processing

1. Introduction

Recently, new trend has been focused on developing methods for depositing bioactive materials on metallic substrates to improve tri-biological, biomedical and mechanical properties of biomedical implants. Various studies developed to consolidate pre-relevant properties of bioactive materials and metals. The light metals or alloys such as Ti and Ti alloys which display excellent mechanical properties such fatigue resistance, toughness and tensile strength are utilized to fabricate surgical implants[1,2]. To maintain the useful properties of biomaterials and enhance their biocompatibility, the surface of metallic substrate is being coated with bioactive materials[3,4]. Hydroxyapatite (HA) coatings on biomedical applications are widely accepted in metallic implants because of its chemical composition near to the natural bone and its excellent biocompatibility[5]. Hydroxyapatite promotes the bone growth and improves fixation of implants which is utilized to treat defected or damaged bones[6]. The chemical form of HA is Ca10 (PO4)6(OH)2 and its main constituents are Ca and P[7]. It can be synthesized or natural. The Ca/P ratio is made 1.67 (Ca/P ratio in bones is 1.65) for pure synthesized HA which is most available and cheaper and assists the growth of the bone[8]. The biocompatibility of HA with hard tissues and soft tissues (muscle, gum and skin) is an essential advantage[9]. The degree of porosity is another factor which defines the quality of HA implants. The bone tissues and cells are grown more on the porous parts, which results in improved bonding and fixation.

The resorption of HA is affected by the degree of crystallinity of bioactive material interfaced with liv-

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ing tissues. The resorption rate decreases with higher degree of crystallinity and offers a desirable longer life[10]. S. Overgaard et al. found that low crystallinity (50%) of HA had shown better bonding with bone than high crystallinity (75%) level after 16 weeks as shown in Figure 1[11]. The poor mechanical properties and brittleness of HA faces problems in load bearing implants such as knee joint and hip joints. The comparison of mechanical properties of HA and cortical bone is shown in Table 1[12]. Due to high Young's modulus and low fracture toughness, its application is generally hindered to non-load bearing implants unless mixed materials offering better mechanical properties. The stimulation and faster development of bone cells between human tissue and bone implant is due to the osteoconductive and bioactive properties of HA and that leads to the rapid biological fixation of implants[13]. To ensure long term fixation in dental and artificial implants, the adhesive strength between metal substrate and HA is necessary, but HA exhibit hazardous mechanical properties such as toughness and adhesive strength[14].

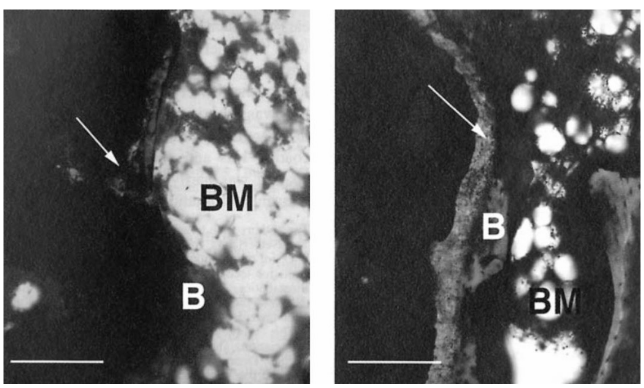

Figure 1. Bone growth on **(a)** 50% **(b)** 75% crystallinity HA[11].

Table 1. Mechanical properties of HA and bone[12]

Material	Young's modulus, GPa	UTS, MPa	Fracture Toughness MPa.m$^{1/2}$
HA	80-120	40	0.6-1
Cortical Bone	1-20	50-150	10-12

The significant difference in the Coefficient of Thermal Expansion (CTE) results in poor adhesion between metal substrate and HA coating. The factors like low crystallinity, poor mechanical properties resulting in peeling and degradation, disturbed the clinical performance of HA coatings. Therefore, new coating replacements for HA coating can have better performances in orthopedic implants. In this article, we will discuss about bioactive materials and methods developed to enhance the properties of the implants[15].

2. Biomaterials Application Criteria

An implant material in initial time was viewed as appropriate to supplant natural tissue as it had insignificant or negligible toxicity[16]. Later on the capability to enhance the growth of natural tissue was considered[17]. Later on, the capability to enhance natural tissue growth was considered[18]. To accomplish the objective in terms of material modification, processing route, design, a few examinations have been conducted[19]. The biomaterials utilized for implants should be non-toxic. The increase in metallic ion content in blood is a consequence of cytotoxicity[20]. The bonding between implant material and tissues can be improved with roughness on implant surface[21]. Roughness and porosity on surface of implants is an essential property for osteointegration and improved bone growth[22]. The problem of stress shielding creates serious issues in biomaterials. The bone resorption is caused by stress shielding and this phenomenon emerges when Young's modulus of implant and bone are different as shown in Figure 2[23]. Bioactive materials based on ceramics and metals have improved Young's moduli than trabecular and cortical bones[24]. To address this problem material selection and manufacturing processes have been performed.

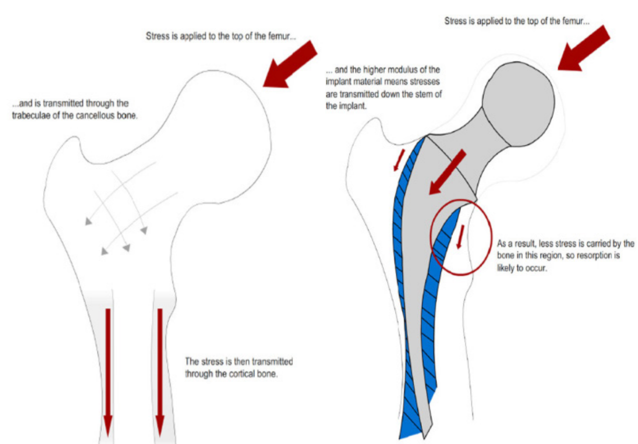

Figure 2. Stress shielding mechanism[23].

3. Coating Replacements for HA Coating

The role of silicon as a cross linking agent in connective tissues and to make bonding between muscle and bone in bioactive materials had been shown in literature[25]. Silicon is engaged in cellular development and gene expression as it performs metabolic function. The strength of hydroxyapatite coating is improved with presence of silica particles by particle mediated reinforcement leading to crack deflection or crack arrest. The mechanical properties of HA coatings has been improved as silicon oxide acts as reinforcing agent.

In recent years numerous researches showed that CaO–MgO–SiO system based glass ceramics were regarded as potential candidates for biomedical applications. The probable single crystalline phases such as diopside (CaMgSi2O6, C3MS2), dicalcium silicate (Ca2SiO4, C2S), wollastonite (CaSiO3, CS), akermanite (CaMgSi2O6, C3MS) have been investigated thoroughly which showed good mechanical properties,, biocompatibility, Osseo integration, cytotoxicity[26]. Recently the researchers showed interest in flourishing multiphase glass ceramics for orthopedic implantations, as they can manage their properties such as abrasion resistance, coefficient of thermal expansion through controlling the composition and heat treatment processes[27].

4. Coating Techniques

- Techniques utilized for coating HA on metallic substrates include,
- Thermal Spray techniques[28]
- Dip coating-sintering[29]
- Ion beam sputtering coating[30]
- Hotisostatic Pressing (HIP)[31]
- Electrophoretic deposition[32]
- Vacuum Plasmaspraying (VPS)[33]
- Biomimetic deposition[34]
- High-Velocity Oxy-Fuel Spraying (HVOF)[35]
- There are other numerous experimental deposition process such as sputter coating[36]
- High velocity airfuel spraying[37]
- Pulsed laser ablation[38]
- Dynamicmixing, dip coating[39]
- Sol–gel[40]
- Electrophoretic deposition[41]
- Biomimetic coating[42]
- Hot isostatic pressing[43]

The problem of early failure in joint replacements after short implantation times due to aseptic loosening is fixed by the industries by implementing the idea of producing HA coatings using plasma spray technique[44]. Further studies showed the problems inherent in the plasma-spraying procedure. The degradation of the initial phases of the HA powder and unwanted phases with poor mechanical properties either in the coating–substrate interface or across the coating resulted due to high temperatures reached during the plasma spraying process[45,46]. The micrometric parts of the coating may separate from the prosthesis and damage tissues due to the reason of brittleness of HA[47]. So, plasma-spray technique was substituted by HVOF (high-velocity oxy-fuel spray), using lower temperatures and subsequently, resulting in a lower degradation of the coating[48].

A bio implant should remain intact in human body for the period of 15 to 20 years in case of older patients and more than 20 years in case of younger patients. The highly corrosive body environment which includes blood and other constituents of the body fluid like water, amino acids, proteins, chlorine, plasma, sodium have detrimental effects on biocompatibility and mechanical properties of implant[49]. The introduction of additional ions in the body by dissolution of surface oxide film can be avoided by good corrosion resistance of bio implant[50].

5. Cryogenic Processing

Cryogenic machining offers better functional performance, life and sustainability to biomedical implant materials. Cryogenic processing is a sustainable, environmental friendly and non-toxic means to enhance the properties of biomedical implants[51]. The process utilizes liquid nitrogen to absorb heat generated during processing. The cryogenic processing is most appropriate in biomedical, aerospace and automobile engineering where hard to machine components are utilized to manufacture good durability products[52]. The important advantage of cryogenic processing is the removal of secondary cleaning processes usually elimination of contamination from flood coolant[53]. In recent research, cryogenic processing has been found to improve all relevant characteristics of orthopedic implants like Co alloy, Mg alloy, Ti alloy and NiTi alloy as shown in Table 2[54]. To obtain improved functional performance and biocompatibility in orthopedic implants, proper attention has to be given to optimize the processing parameters. The remarkable control over the heat generated during processing, which results in damage of thermal surface and subsurface during conventional lubricating/cooling strategies like MQL or flood cooling is the key mechanism by which exceptional improvements are attained[55].

Table 2. Benefits and applications of cryogenic processing[52]

Alloys	**Typical applications**	**Benefits of cryogenic processing**
Co alloys	Permanent implants	Reduced burnishing tool-wear, nano structured surface layer; and improved wear resistance
Mg alloys	Self-absorbing implants	Multi-millimeter SPD layer, Improved hardness, corrosion resistance and compressive residual stresses.
NiTi alloys	Stents, clamps and staples	control over phase transformation behavior, significantly increased tool-life,
Ti alloys	Corrosion resistant implants and hardware	Improved micro structural characteristics (nano-grains likely) and hardness.

6. Research Gap

Recently, numerous examination works concentrated on creating materials for bone implants with longer life expectancy (over 25 years). Likewise, more studies are expected to enhance the performance and biocompatibility of biomaterial alloys. The present implants life is 20-25 years and the goal is to achieve 40 years to limit the revision surgeries. The lack of improved adhesion strength with coating methods still lack in meeting improved life spam. The issue of coating separation and lamination during implanting process will be solved with improvement in adhesion strength. Studies should focus on coating of HA on metallic implant using different coating methods have promising potential in orthopedic implants. A new trend is to improve the corrosion and wear resistance of biomedical implant by developing the coatings from High Velocity Oxy-Fuel (HVOF coating technique).

7. Conclusion

Issues concern the material processing and metallurgy characteristics have been reviewed and discussed to meet the requirements for medical implant applications using existing manufacturing process. In perspective of the above showed examinations, it can be concluded that regardless of an extraordinary assortment of techniques expounded for preparation of HA which are to be utilized as bone scaffolds and implant coatings, there is as yet an immense interest for building up a simple, efficient, and green method of their production. Advancement of reasonable bone scaffolds is a principal undertaking of great importance in the bone tissue designing in order to aid restoring of the damaged, diseased or disintegrated tissues. The metal substrate failed to demonstrate the properties of bioactivity and durability in corrosive environment. Likewise, research showed release of ions from metal implants which are hazardous when implanted in human body. In contrary, bioceramics revealed excellent mechanical properties, biocompatibility and bioactivity.

In order to consolidate the bioactivity of HA and mechanical properties of metal implants, several methods have been developed to deposit bioactive materials on metallic substrate. Cryogenic processing has been proved to be an alternative method for enhanced performance of bioactive materials. Significant improvements in the surface integrity of biomaterials have been achieved, such as:

- Improved residual compressive stresses
- Improved corrosion resistance, wear resistance and surface hardness.
- Beneficial phase transformations of the processed surface layer
- Nano-structured surface layers

The research trend is to display enhanced durability and performance of orthopedic implants as the present methods still lack to meet the objectives

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