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FUNCTIONALLY GRADED DENTAL IMPLANTS: A REVIEW OF STRUCTURAL DESIGN AND FABRICATION TECHNIQUES

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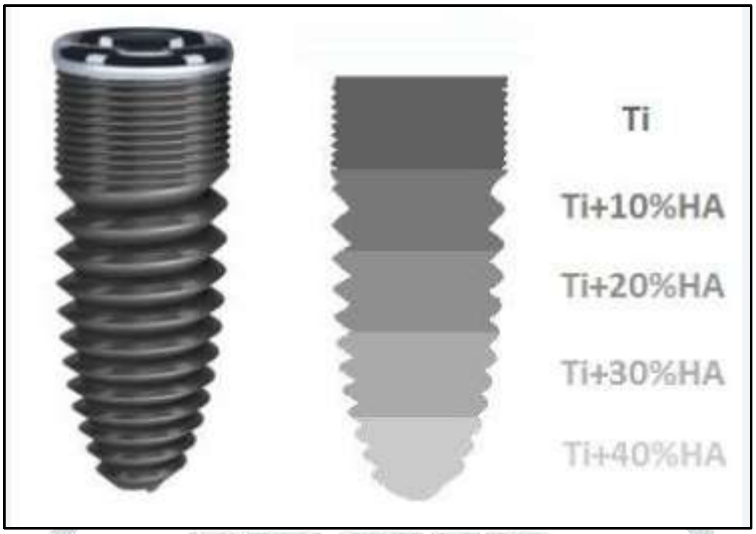
Abstract: Functionally graded material (FGM) is a clever way to develop composite materials to increase their durability over time. The primary feature of a FGM is its improved characteristics brought about by a progressive change in composition and microstructure over its dimensions. Numerous domains, including thermal barrier coatings, the power sector, biomechanical, automotive, aerospace, mechanical, civil, nuclear, aeronautic, and naval engineering, have used this methodology. Solid titanium, which is frequently used in conventional dental implants, frequently causes mechanical incompatibility with the surrounding bone because of unequal stiffness, leading to stress shielding and decreased osseointegration. By gradually changing their composition, porosity, or structural characteristics, Functionally Graded Dental Implants (FGDIs) seek to close this gap and maximize their biomechanical and biological performance.
This article provides an overview of FGMs, their application in implant dentistry, and their mechanical performance.

Index Terms - Functionally graded implants, osseointegration, biomaterials

INTRODUCTION

Nowadays, dental implants are frequently used to correct tooth loss by improving both function and appearance. A high success rate of 90–95% has been shown despite the polluted environment of oral surgery [1]. Dental implants can fail for a variety of reasons, including the implant itself, the patient, and the surgical technique. The implant should have little risk of infection, adequate osseointegration, and appropriate mechanical qualities. The success of the implant is impacted by several factors, including age, smoking, alcohol use, gingivitis, bone quality, metabolic and systemic illnesses, and the periodontal state of natural teeth. The surgical technique is harmed by perioperative bacterial infection and surgical trauma [1].
Because titanium (Ti) and its alloys have excellent corrosion resistance, high strength/density ratios, and are non-toxic, they make up most dental implants now in use. Even though Ti's elastic modulus is like that of bone when compared to other metallic materials, the mechanical mismatch between Ti and bone results in a stress shielding effect and implant loosening [5].

The most efficient method of bringing Ti's elastic modulus closer to bone's is through its porous construction. Because of its bone-compatible mechanical qualities, porous titanium helps fixation by allowing bone tissue to grow into the pore.



Five layered FGM Dental Implant

The idea of FGM first surfaced in Japan in 1984 during the space aircraft project as a suggested thermal barrier material that could survive a temperature differential of 1,000 K across a cross section of less than 10 mm and a surface temperature of 2,000 K. 9.10 Since then, FGM thin films have undergone extensive development and are practically a product of commerce. FGM is often a composite material made up of two or more constituent phases with a continually changing distribution, which may be seen in their shape, orientation, and volume or weight percentage.

Dental implants classified as functionally graded (FG) are a sophisticated kind of implant made to have characteristics like stiffness and biocompatibility that progressively change throughout its structure. By adapting the implant's characteristics to the requirements of various bone areas, this design seeks to enhance osseointegration, accomplish improved biomechanical performance, and lessen stress shielding of the surrounding bone. Because FG implants don't have abrupt material changes as traditional implants do, they blend in better with the host bone and provide more stability over time.

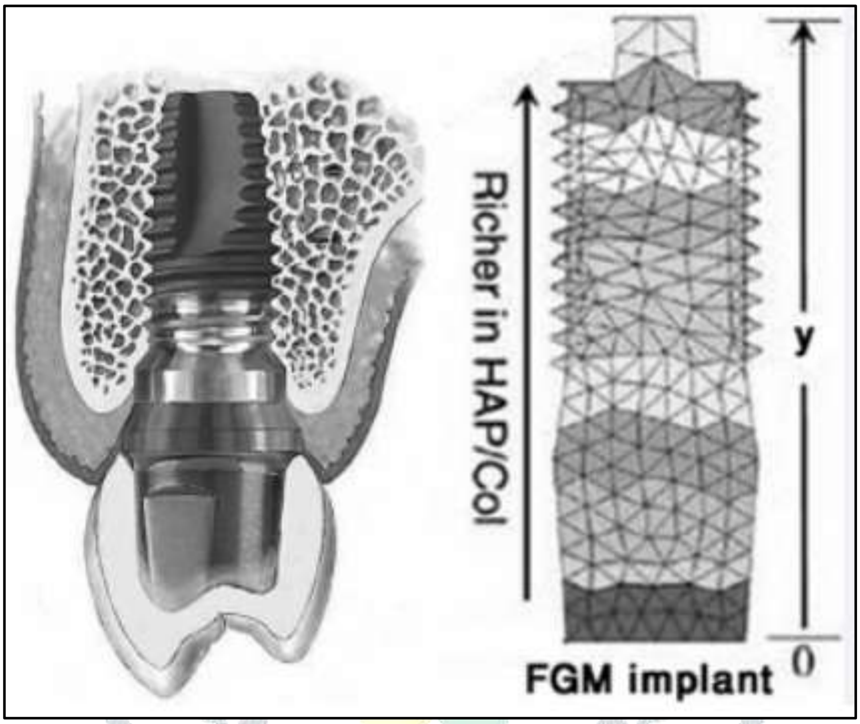
The idea behind FGMs is to create a composite material with two or more constituent phases by changing the microstructure of one material to another with a certain gradient, resulting in a product that combines the best qualities of both parent materials. 12 In the case of continuous grade structure, composition and microstructure vary continually with position, although

The stepwise microstructure feature creates a multilayered structure with an existing interface in a gradual way.

across distinct strata (Fig. 2). A smooth transition for the FGM can be determined by measuring the variation in hardness, fracture toughness, and cellular adhesion across the cross section. For example, the FGM of HAp–Al2O3–yttria-stabilized Zr nanocomposite has unrestricted surface bioactivity and increased bulk toughness, making it a good choice for bone implants.

Functionally graded dental implants (FGDIs) are a cutting-edge method of using dental biomaterials that are intended to replicate the gradient structure found naturally in teeth and bone. These implants are designed to gradually change in composition and microstructure, which improves their biocompatibility and mechanical qualities.

STRUCTURE OF FUNCTIONALLY GRADED IMPLANTS



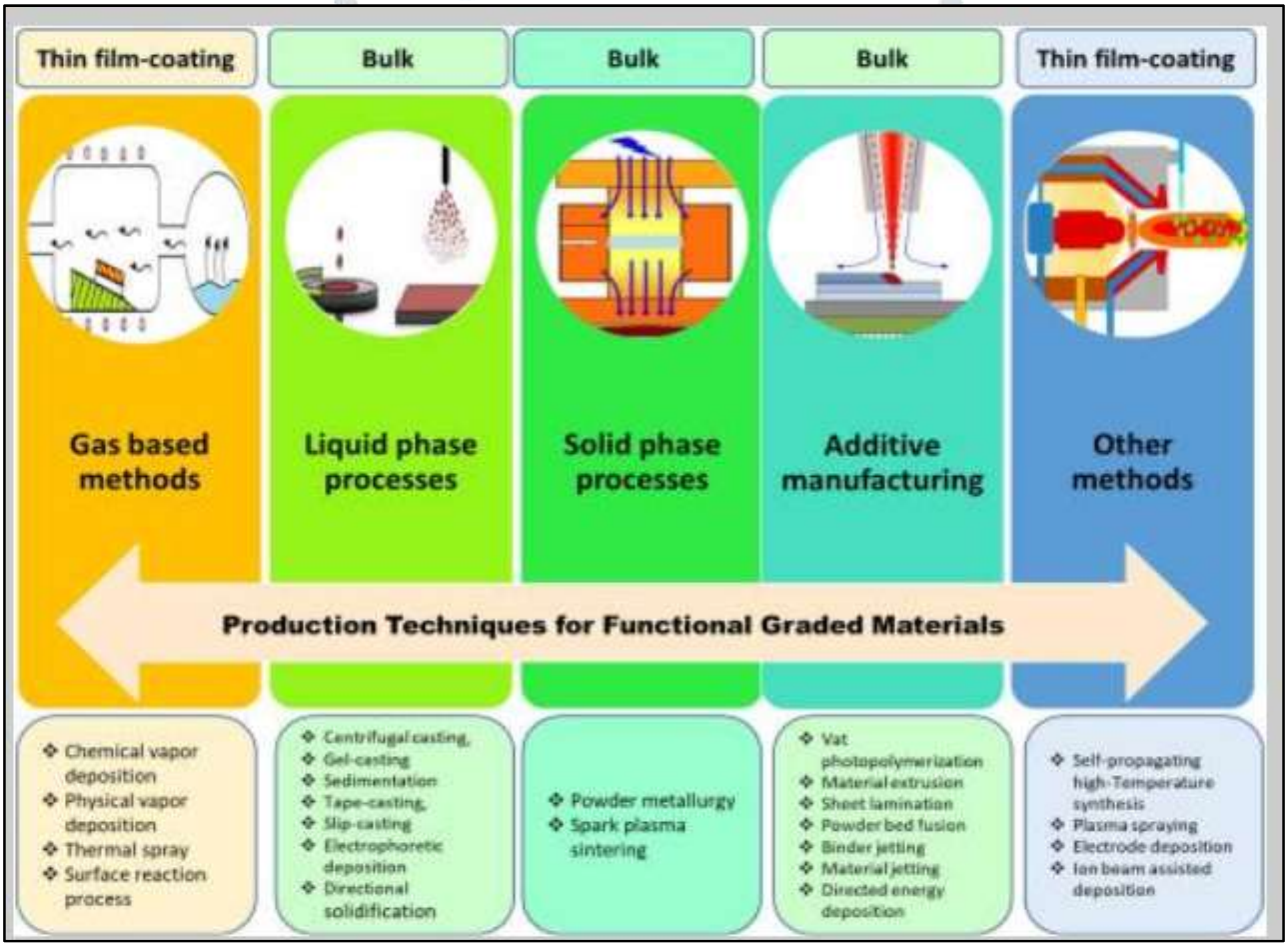
FGM Implant structure

Observations reveal that the architecture of many natural tissues and organs—such as snail shells, bamboo, bone, and skin—are functional gradients rather than uniform materials. If each layer of an organ or tissue performs one or more specific tasks to meet local functional needs, the organ or tissue is said to be functionally graded. Therefore, FGM should be incorporated into a successful dental implant idea in order to restore the natural functioning.

A cylindrical form with axially changing content was created for the FGM dental implant. Since the occlusal force acts immediately on the top and is subsequently conveyed to the lower sections implanted into the trabecular bone, where more biocompatible materials are preferred, the upper part possesses the strength and mechanical qualities required. Because implant failure results from a lack of biomechanical bonding between the implant and the surrounding jawbone, the lower portions of the implant should have a high osteoconductivity and a good bone-to-implant contact to promote quick osseointegration and bone regeneration. Additionally, overload or inadequate strength and mechanical characteristics may cause the implants to fail. Therefore, designing appropriate mechanical qualities for the top portions of FGM dental implants is one potential remedy.

MANUFACTURING METHODS

- GAS BASED TECHNIQUES
- LIQUID PHASE PROCESS
- ADDITIVE MANUFACTURING METHODS
- SOLID PHASE PROCESS



A.Gas-based techniques:

1. Chemical vapour deposition

One popular technique for creating functionally graded materials (FGMs), especially for dental implants, is chemical vapor deposition (CVD). This method creates solid coatings on a substrate, usually titanium or its alloys, by introducing gaseous precursors, such acetylene or methane, into a heated chamber where they break down. It is possible to carefully regulate the deposition parameters, including temperature, gas composition, and flow rate, to produce a slow change in the material's characteristics during the coating, such as hardness or bioactivity. The ability to provide near-net form coatings that reduce the need for post-processing, low processing temperatures, and continuous compositional gradients are some of the benefits of CVD in FGM manufacturing. Still, to use this approach for dental implant applications, issues like the intricacy of process control and possible environmental issues with precursor gases need to be resolved.

2. Physical Vapor Deposition

Thin, functionally graded coatings are often applied to dental implants using gas-based Physical Vapor Deposition (PVD) methods including Chemical Vapor Deposition (CVD) and Magnetron Sputtering. By converting materials from a condensed phase to a vapor phase, these techniques create a thin layer that condenses onto a substrate. In order to customize material gradients to meet the mechanical and biological needs of the implant site, variables such as temperature, gas ratio, and flow rate may be accurately adjusted to alter the composition and characteristics of the deposited layers.

Implant surfaces are coated with ion-substituted calcium phosphate-based coatings, including Hydroxyapatite, using PVD techniques like magnetron sputtering. It has been demonstrated that these coatings have a favorable impact on cell interactions, such as adhesion, differentiation, and proliferation. The PVD technique is beneficial because it can create a variety of coatings in an eco-friendly manner, producing long-lasting coatings with desirable qualities. Functionally graded HA/Ti-6Al-4V coatings are made in three layers using a different PVD method called plasma spraying. These coatings are appropriate for biomedical applications because they show progressive differences in microhardness, Young's modulus, microstructure, and porosity between layers.

B. Liquid Phase Process

1. Electrophoretic deposition

Functionally graded materials (FGMs) for dental implants may be made using the flexible and reasonably priced Electrophoretic Deposition (EPD) process. This method involves applying an electric field to a stable colloidal solution of charged particles, which migrates and deposits the particles onto a conductive substrate that has the opposite charge. This leads to the development of a consistent and sticky layer.

EPD is used in dental implants to create multilayered hydroxyapatite (HA)-chitosan composite coatings, which is particularly noteworthy. HA-chitosan coatings with thicknesses ranging from 2 to 200 µm were deposited using cathodic EPD in research by Sun et al. (2009). The enhanced blood compatibility of these coatings made them appropriate for surface modification of dental implants.

C. Additive manufacturing methods:

Especially in the biomedical industry, additive manufacturing (AM), sometimes referred to as 3D printing, is a revolutionary method for creating functionally graded materials (FGMs). With AM, intricate, patient-specific implants may be made without the need of conventional tools or assembly procedures. This feature is particularly helpful in dental implantology, where unique anatomical differences call for tailored treatments. A 3D Computer-Aided Design (CAD) model is the starting point of the procedure. It is then transformed into digital data and thinly sliced using specialist software. By providing precise control over the material composition and structure, these layers direct the AM system as it builds the implant layer by layer. To produce FGMs, this layer-by-layer structure is essential since it allows for the progressive change of material characteristics.

Electron beam melting (EBM) and selective laser melting (SLM) are two well-known AM processes used in the manufacturing of metallic FGMs. EBM uses an electron beam in a vacuum setting, whereas SLM uses a powerful laser to melt and fuse metallic particles. Both techniques may create intricate, thick structures that are appropriate for load-bearing applications with great accuracy. Implants with improved osseointegration potential and optimal mechanical characteristics can be made thanks to these methods.

D. Solid Phase Process

1. Powder metallurgy

A well-known solid-phase method for creating Functionally Graded Materials (FGMs), especially for dental implant manufacturing, is powder metallurgy (PM). To create a dense, uniform structure, graded powder combinations are stacked one after the other, then compacted and sintered. Powder weighing, mixing, compaction, and sintering are the main phases of PM; other post-processing procedures like coining or resintering are optional and can improve the material's qualities.

The capacity to create intricate forms from metallic or ceramic powders is one of PM's benefits in FGM fabrication, which makes it perfect for FGMs with solid constituents. This feature is especially helpful for dental implants, where biocompatibility and customized mechanical qualities are essential. PM makes it possible to optimize implant properties to fit the mechanical and biological needs of the surrounding bone tissue by modifying the structure and content of the graded materials.

2. Spark Plasma Sintering

Pulsed direct current is used in the quick, solid-state sintering process known as Spark Plasma Sintering (SPS) to densify powder compacts. Functionally graded materials (FGMs) having specific qualities for biomedical applications, such dental implants, can be created using this technique.

A graphite die and the powder compact are subjected to a pulsed DC current in SPS, which causes internal heating and quick sintering. This method produces dense materials at relatively low temperatures by enabling high heating rates (~1,000 K/min) and brief sintering periods.

Quick complete densification is beneficial for maintaining the integrity of components that are sensitive to temperature, such as hydroxyapatite (HA).

CONCLUSION

By incorporating incremental changes in material composition, structure, and mechanical qualities, Functionally Graded Dental Implants (FGDIs) offer a substantial improvement in implantology. In contrast to conventional metallic and ceramic implants of uniform stiffness, this gradient design successfully resolves the long-standing problem of stress shielding and achieves superior mechanical compatibility with surrounding bone tissue.

To enhance osseointegration and lessen stress behaviour, many parallel studies based on the FGM idea are now being conducted on dental implants coated with HA, Zr, and its oxides. Improved biomechanical, microstructural, and compositional compatibility with natural bone may result from the FGM model. The FGM principle is also used in PFM restorations, where a FGM composite interlayer strengthens the metal–ceramic link and dramatically lowers metal–ceramic failure.

This study aims to provide a comprehensive overview of FGMs, including their characterisation, technology and production processes, and dental applications.
For dental implant applications, a good mix of appropriate mechanical qualities, excellent biocompatibility, and antibacterial activity is needed. Throughout the area where the implant is positioned, the tissue it interacts with changes. As a result, the intended functions' order varies along the cross-section.

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