Functionally graded materials –An overview

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Abstract:
Modern dentistry aims in restoring the patient to normal form, function and aesthetics with minimal intervention. Dental implants are one of the minimal invasive treatment options for restoring the missing dentition. Titanium has emerged as an implant biomaterial by satisfying all but one criterion for success, which is its stiffness value which is far greater than bone. This mismatch can lead to stress shielding and eventually implant failure. There is a huge development in the implant biomaterials since decades, but an implant with single composition cannot meet all the requirements in the oral cavity. So, the implants should be functionally graded i.e., composed based on function to achieve optimum results. Through this review, we would like to summarize the functionally graded materials, their manufacturing techniques and their use as implant materials

Keywords: Functionally graded materials, implants, stress shielding, bone modelling, osseointegration.

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Introduction

Dental implantology has created a paradigm shift in the management of edentulousness. This was almost entirely due to the efforts of Brånemark and Albrektsson who respectively, discovered and detailed in the '60s, Osseo integrability of Ti and the criteria for ascertaining its success. This pioneering work was soon expanded by several others and eventually resulted in the origination of a super-speciality called Dental implantology. In the decades that followed it was evident that despite the unparallel success of Titanium as the material of choice for implants, there still remained certain areas that needed improvement. The science of implantology based on Titanium was therefore, not a finished endeavour but work in progress. Three areas that were identified for further improvement

1.The prolonged time interval between implantation and restoration placement.
2. Design aspects
3. Material aspects

The time interval as originally proposed by Brånemark was between 3-6 months between implant t and restoration placement. This temporal space was required for the implant to Osseo-integrate. An unsatisfactory outcome from a patient's perspective. Overcoming this hurdle required the development of strategies to decrease the time lag. Many such techniques are available in literature and they have been successful in varying degrees in overcoming these problems.[1]

As regards the second issue several designs have been proposed and have met with varying success rates.[2] However, the third has not been amenable to a complete resolution despite the best efforts of researchers. Till date no material other than titanium, with or without surface modifications has been successful as an implant material. But its Young's modulus(E) value(stiffness), which is several times greater than bone has posed the almost intractable problem of Stress Shielding

The Young's modulus(E) of a material is a measure of the stiffness of a given material. The greater the mismatch in E between two materials in contact and undergoing simultaneous loading, the greater the chance for 'STRESS SHIELDING'. This is a phenomenon where the stiffer material shields the less stiff one from applied stresses; in this case bone. Bone requires a certain minimum stress for maintaining its health[1]. Thus, a stress shielded bone surrounding an implant can undergo resorption and lead to implant failure.

Therefore, an ideal implant material even while being bio-compatible (Osseo integrable) must have a Young's value comparable with bone to preclude stress-shielding. This requires an entirely new class of material; one that even while possessing strength and biocompatibility has a structure that varied along its body. A stronger exogenous region for accommodating stress and a relatively less strong endogenous region which was biocompatible but closer in E value to bone; i.e. a FUNCTIONALLY GRADED MATERIAL (FGM)

This overview article is an attempt to explore the concept of an FGM and its application in dental implantology. The topic will be addressed under the following headings:

- The concept of FGM
- Methods adopted to fabricate such materials followed by a description of the various candidates currently being developed for fabricating dental implants.
- Discussion
- Conclusion

THE CONCEPT OF FGM:

Brief history:

The concept of a functionally graded material (FGM) had its origin in Japan during the mid '80s. Japan needed a differentially heat resistant tile for its space programme. A tile capable of withstanding 2000K on the outside and 1000K on the inside across a 10 mm thickness. This demand could not be met by using a uni-compositional material as no single material would be able to satisfy this unique requirement. Thus, a material that had a differential thermal resistant property was developed. This was the Functionally Graded Material which had a superficial resemblance to traditional composites because it was multi-component in nature. However, it differed from composites as, instead of an abrupt change in properties from one component to another there existed a gradation in composition, structure, porosity etc within the material. FGMs are currently considered as the next generation of advanced materials after composites. (Figure 1)

Definition of an FGM:

FG Materials are those with a changing composition, microstructure and porosity across the bulk volume of the material.

It has been alternatively defined as 'a two-component composite characterised by a compositional gradient from one component to another.

Classification of FGMS:

FGMs were originally classified by researchers under traditional composites into six groups[3,4].: based on 1. State during processing,2. FGM structure 3. FGM type 4. Nature of gradient 5. main dimensions 6. Field of application

There are different forms of FGM:

Chemical composition FGMs: these have gradually varying composition varying according to the spatial position within the material. This could be in the form of a uni-phase or polyphasic material.

Porosity gradient FG material: these are functionally graded in terms of porosity values. The distribution of porosity being tailored according to specific needs

Microstructure gradient FG material: these materials have a graded microstructure to meet varying demands (Figure 2)

Processing techniques for FGMs

There exists a number of techniques for processing FGMs and they include the following details of which are available in literature[5,6,7,8,9,10,11,12,13]

They include the following.

a. Vapour deposition:

This is used to deposit FGM surface coatings which give excellent microstructures but is limited to giving only surface coatings

b. Powder metallurgy:

FGMs are prepared by this method in the following manner.

Weighing and mixing of powder according to the pre-designed spatial distribution as dictated by the functional requirement, followed by stacking, ramming and sintering

c. Centrifugal method

Gravity is used through spinning of the mould to form the bulk FGM. A graded material results because of the difference in material densities caused by the spinning of the mould

Lamination and infiltration methods:

a. SOLID FREE FORM

Also known as Additive manufacturing technique and its sub categories like LENS (Laser engineered Net shaping) (DLMS- direct laser metal sintering) for metals, stereolithography for polymers, that offers multiple advantages which include:

Increased speed of production, less energy intensive, economical and a flexibility to produce complex structures. While all of the above methods resulted in solid structures many porous FGMs were also developed by techniques like cold isotactic pressing, and spark plasma sintering or hot pressing and sintering.

FGMs for DENTAL IMPLANTOLOGY (Figure 3)

There are a number of potential FGM candidates developed for use in dental implantology. They include the following:

1. Titanium (Ti) – Cobalt FGM
2. Ti- Zirconia FGM
3. Ti- silica FGM
4. Ti-Hydroxyapatite and TiN-Hydroxyapatite FGM

Ti-Cobalt: It was Wataari et al[14] who developed and evaluated the mechanical properties and biocompatibility of this composite. They discovered that this combination had poor osseointegration capability and instead formed a thin connective tissue layer at the material-implant interface. This precluded it from being used as a dental implant material

Takahashi et al (1992)[15] investigated the Ti-Silica FGM for dental use in 1992.They chose Silica owing to its capability to better integrate with Hydroxy-apatite this which led to stronger bond with bone.

The same group also developed a Ti- Zirconia FGM. They noted that Zirconia particulates caused lesser inflammatory reaction than Titanium.

Fuji et al[16,17] successfully prepared a PSZ/Titanium FGM through the hot-pressing route and evaluated its mechanical properties like flexural strength, Young's modulus, and hardness. They found that hardness values decreased with increase in Titanium content.it was also observed that there occurred a chemical reaction between PSZ and Ti at the elevated sintering temperatures which influenced the mechanical properties of the FGM.

But the FGM that has attracted the attention of researchers has been the Hydroxy-apatite /Titanium combination. Hydroxyapatite (HA) is the mineral backbone of bone. Hence any composite involving HA is bound to have better bone binding properties.

Various fabrication techniques have been employed to obtain a HA-Ti FGM Like cold isotactic pressing (CIP)- spark plasma sintering or hot pressing and sintering

It was Watari et al (1997)[18] who first successfully synthesised a Ti-HA FGM for making implants using CIP followed by Argon frequency induction heating.

In order to minimise the degradation of HA at elevated sintering temperatures Kondo et al[17]used TiN instead of Titanium to obtain a FGM. However, they could not demonstrate an improvement in bonding between HA and Ti in the TiN rich region.

Functionally graded ceramic-ceramic materials

Guo et al described the successful preparation of a HA/ZIRCONIA FGM for making dental implants. The sintering caused some changes in the HA but the zirconia remained untouched. The material, they reported had adequate mechanical properties for implant applications.

Porous fgm for dental implants:

The rationale behind the formulation of these materials were two-fold. Firstly, it would enable mechanical properties of the material toapproximate that of bone owing to a structural similarity to bone, and secondly, the rough, porous structure would increase fibroblast attachment and bone formation.

Thieme et al [20]produced porous Ti FGMs for orthopaedic implants using powder metallurgy methods. This material they reported has an E value close to bone thus obviating the stress shielding effects of such materials.

Kutty and Bhaduri[21] developed Titanium based FGMS with graded porosity while maintaining

a dense core of the metal. These materials demonstrated better stress transfer behaviour than non-porous metal.
Suk et al[22] prepared a porous Titanium based FGM with good pore connectivity,
Krishna et al[23]used Laser engineered Net shaping (LENS) to fabricate dental implants with graded properties that related closely to the properties of bone.
The arrival of DMLS (direct metal laser sintering) an additive manufacturing process has considerably increased the field of application of Titanium alloys by allowing implants to be manufactured more economically. This technique uses laser sintering to build up objects from metal powder, which require very little if any, post processing of the finished product, Traini et al[24] used this method to make dental implants which they subsequently acid etched to improve surface properties.

Discussion and future considerations:
Titanium has played a major role in creating a paradigm shift in the management of edentulousness. This is owing to it ability to osseointegrated with bone. But Titanium has a major disadvantage. This is the mismatch in E values between metal and bone. This mismatch leads to a phenomenon termed as ‘stress shielding’ which eventually causes bone resorption around implants and its consequent failure. The formulation of FGMs has been instrumental is addressing this problem.
An FGM is a material which is characterised by a compositional gradient throughout its bulk. This makes it superficially resemble a composite, which it is not. This is because in FGMs there is a continuous gradation of properties whereas in composites there is an abrupt change in properties at the interface between the two components. These materials are important to dental implants because it is now possible to have an implant which had strength and biological properties as required in the same material. Strength properties in areas where stress is expected to be high and less where it interacts with bone which essentially helps nullify the stress shielding phenomenon.
Many combinations of materials and a variety of processing techniques have been developed to manufacture FGMs in both solid and porous forms. Among the various chemical combinations developed are Ti-Co, Ti-Zirconia, Ti- PSZ, and Ti-HA. The Ti-HA combination hold much promise as HA is native to bone and the availability of a HA as a component of an implant material is definitely bound to improve osseointegration.
The processing of FGMs has been challenging, however a number of them have been developed over the years as described above. Some of them are Vapour deposition, powder metallurgy, centrifugal method etc etc. To this newer technique like LENS, DMLS have also been added.
But even while such specialised materials are being developed, the non-availability of a clinically viable product is a drawback. Therefore, if FGMs have to be of clinical use then it is imperative that s prototypes fabricated from FGMs be made available for clinical trials at the earliest. This then is the agenda for the future.

Conclusion
Titanium has had a tremendous influence on dentistry. But the stiffness of titanium being much greater than bone can lead to stress shielding and eventual implant failure. The development of a new class of material, the FGMs, has the potential to tackle this problem. These are materials whose mechanical properties can be graded, within the same sample, to meet varying functional demands. This article was an attempt to present the current state of these materials, and what the future demands from this exciting field.

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Figures

Figure 1

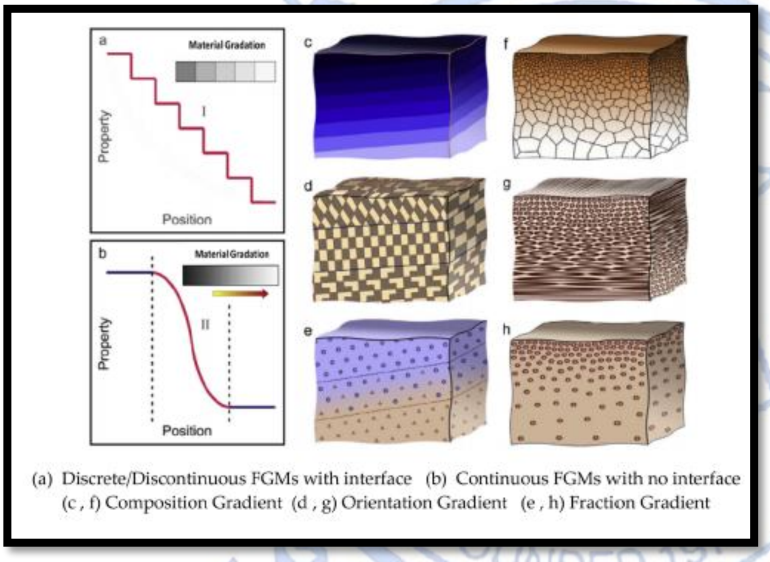

Figure 2

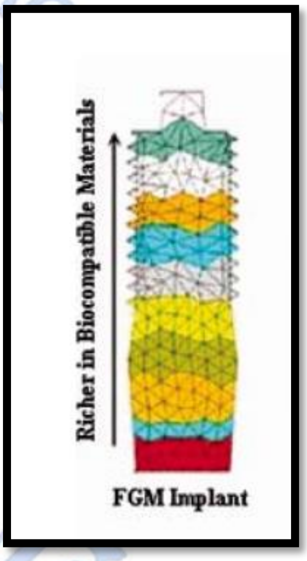

Figure 3