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The Smart Future; Innovations in Materials

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Abstract

With the advent and innovation in the fields of nanotechnology and biomedicine new and promising frontiers are being introduced regularly, these aim for improved efficiency and reliability by inculcating the use of smart materials and structures. Biomedical applications of smart materials include their use in tissue engineering, cell culture, biomimetic actuators etc. Smart materials have revolutionized many areas of dentistry including orthodontic wires, coils and springs. Cercon smart ceramics, Resin modified glass ionomer cements (RMGIC), Smart composites. These offer natural esthetics coupled with excellent durability and biocompatibility. These innovations in material science have already marked the beginning of the smart future of dentistry. This review provides a selective summary of smart materials in dentistry.

Keyword: smart materials; smart composites; cercon, biocompatibility; resin modified glass ionomer cements (RMGIC).

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1. Introduction

Since its beginning material science has evolved from the use of inert materials to materials with specific functions and finally to smart materials. Smart or intelligent materials are materials that are highly responsive have inherent capacity to sense and respond to stimuli and environmental changes. Smart materials can be defined as “materials that have properties which may be altered in a controlled fashion by stimuli such as stress, temprature, moisture, pH, electric or magnetic fields” A key feature of smart materials is their ability to return to original state after the removal of the stimulus [1]. Materials designed for long term use in body or oral cavity are perceived to be “passive” in nature and are designed so that there is no interaction with the internal environment [2]. But with recent advancements in material properties it is obvious that materials that are “active” such as glass ionomer have better properties such as fluoride release, this smart behavior was noted by chance over time as in the case of other shape memory alloys and polymers that have been prevalent in dentistry for long periods of time [3].

2. Requiremenst of materials

To achieve a specific objective or function for application the material or alloy has to befitting certain prerequisites related to the following properties: [4]

- **Technical properties:** these include the mechanical characteristics such as plastic flow, fatigue, yield strength and behavioral properties such as damage tolerance, electrical and heat resistance.
- **Technological properties:** these encompass the manufacturing, forming, welding abilities along with thermal processing, workability, automation and repair capacities.
- **Economic criteria:** this is related to material and production cost, supply, expense and availability.
- **Environmental characteristics:** these include features related to toxicity and biocompatibility

3. Classification of smart materials

According to Valiathan2007 article about bio-smart materials, these can be generally categorized as [5, 6].

I. Passive smart materials these respond to external changes without external control [7].

- GIC
- Resin Modified GIC
- Compomers
- Dental Composites

II. Active smart materials these utilize a feedback loop to enable them function like a cognitive response through an actuator circuit [8].

1. Restorative Dentistry

- Smart GIC
- Smart Composites
- Ariston Phc

2. Prosthetic Dentistry

- Smart ceramics
- Smart impression materials

3. Orthodontics

- Shape memory alloys

4. Pediatric and Preventive Dentistry

- Fluoride releasing pit and fissure sealants
- ACP releasing pits and fissure sealants

5. Endodontics

- Nitti rotary instruments

6. Smart Fibers for Laser Dentistry

- Hollow-core Photonic Fibers

III. Very smart materials that sense a change in the environment and respond (by altering one or more of their properties)

IV. Intelligent materials that integrate the sensing and actuation functions with the control system.[9]

4. Properties of smart materials

The idea behind smart materials is to produce non-biological structures that will mimic the biological systems with optimum functionality by virtue of their adaptive capabilities and integrated designs. Smart materials can detect the changes in the environment around them and respond. In general these are:

- **Piezoelectric:** they have direct and converse effects, when subjected to an electric charge or change in voltage, piezoelectric materials will undergo some mechanical change.
- **Electrostrictive:** similar to piezoelectric, but the mechanical change is proportional to the square of electric field. This produces displacement in the same direction.
- **Magnetostrictive:** the material undergoes an induced mechanical strain when subjected to a magnetic field. They can also be used as sensors or actuators.(e.g. Terfenol-D)

- **Shape Memory Alloys:** when subjected to a thermal field this material wil lunder go phase transition to produce shape changes. At low temperatures it's in 'martensite' form which changes to 'austenite' when heated.(e.g. Nitinol)
- **Optical Fibers:** these use intensity, frequency, phase or polarization to measure strain, temperature, electrical/magnetic fields, pressure and other quantities. They are excellent sensors.
- **Thermochromic:** they change color with change in temperature.
- **Photochromic:** they change colors with response to variations in light conditions.
- **PH Sensitive:** they change their shape with alterations in pH.
- **Biofilm Formations**: presence of biofilm on the surface of material alters the interaction of surface with the environment

5. Biomedical and other applications

Recent advances in the designs of polymers have created new avenues for use in the field of biomedical applications. Stimuli-responsive changes in shape, surface characterization, solubility, formation of an intricate molecular self-assembly and a sol-gel transition has enabled several applications in the bio diverse fields of tissue engineering, cell culture [10]. Some of which are mentioned below:

- **Smart pressure bandages**: polyethylene glycols when bonded to fibrous materials such as cotton or polyester possess the property of thermal adaptability and reversible shrinkage [11].when the material is exposed to liquid it shrinks this property is incorporated into pressure bandages that contract and apply pressure when exposed to blood [8].
- **Smart Suture**: this is the practical application for biodegradable plastics with shape memory as the material ties itself onto a perfect notch [12].
- **Hydro gel**: hydro gel exhibits plastic contraction with change in temprature, ph, magnetic or electric filed and have numerous applications e.g. soft actuators in biomedicine for controlled drug release [13].
- **Smart shirts**: developed by Gerorgiatech "smart shirt" Is a wearable motherboard that has optical and conductive properties integrated into the garments. This monitors the heart rate, EKG, respiration, temperature. It can also signal the nature of wound and analyze their extent [14]. Hence it has wide applications in designing outfits for the astronauts and military personal.
- **Vibration reduction in sports goods**: the new generation of sports goods such as tennis rackets, golf clubs, baseball bats, ski boards etc have been introduced to reduce the vibration thus increasing the users comfort and reducing injuries [15].

6. Smart materials in dentistry

As already mentioned most of the smart materials in dentistry were discovered by chance rather than by design[3]. They were termed 'smart" as they are consistent with the newer generation of materials that support the remaining tooth structure.

The smart materials are bio-mimetic in nature, as they mimic the natural tooth substance such as enamel or dentine better and adapt to the ever changing oral environment [16]. Some of the materials already being used in dentistry are:

6.1 Shape memory alloys

The shape memory effect was first observed in copper zinc and copper tin alloy by Greninger and Mooradian in 1938, but in early 1960 Buehler discovered and patented Nitinol (Nickel titanium naval ordnance laboratory) a nickel titanium alloy [17].

In dentistry the shape memory alloys are widespread because of their super elasticity, their shape memory, their good resistance to fatigue and wear and their excellent biocompatibility. All these properties led to their extensive use in orthodontics. The shape memory alloys apply continuous gentle forces within physiological ranges over longer periods of time.

6.2 Smart composites

Smart composites contain ACP (amorphous calcium phosphate). ACP is a biologically important calcium phosphate that exhibits rapid conversion to crystalline hydroxyapatite [18]. The hydroxyapatite is the basic building block of enamel and is also the major constituent of the inorganic part of dentine. During the process of caries, as enamel is undergoing progressive demineralization, incorporation of any material that can potentiate remineralization will arrest the carious demineralization [19]. Indeed, remineralizing agents such as ACP in conjunction with CPP (Casein phosphopeptide), have been incorporated in dentifrices and have been shown to inhibit enamel demineralization and augment remineralization in laboratory studies [20].

ACP is incorporated into resins to fabricate composites that have extended time release nature to act as a source of calcium and phosphate [21]. This is possible because at neutral or high pH the ACP is present but once the pH falls below 5.8 such as during a carious attack the ACP is converted to hydroxyapatite and precipitates thus replacing the hydroxyapatite lost from the tooth due to the acid attack.

Smart dentifrices:

Smart dentifrices containing bio-active glass have been developed and marketed in recent years such as Sensodyne Repair and Protect toothpaste which also contains fluoride along with the active ingredients [22-24]. The active ingredient is the bio-active glass which was originally developed by Hench as a bone regeneration agent in 1969 [25]. The primary constituents of most bio-active glasses used in dentistry as well as bone regeneration are sodium, calcium, phosphate and silicon (phospho-silicate) [26]. Bio-active glasses unlike other technical glasses are characterized by their reactions when incorporated in body fluids. The reactions involve a rapid release of sodium ions that is concomitant with the dissolution of calcium, phosphate and silicon on the biologically active surface of the bio-active glass. This reaction results in the formation of a silica-rich gel on the surface of the glass which in turn, facilitates the deposition and formation of a calcium phosphate layer at the interface between the bio-active glass and body tissues. This process results in the crystallization of hydroxyl-carbonated apatite (HCA) which leads to dental hard tissue remineralization [27]. Bio-active glass containing toothpastes have also been shown to alleviate the symptoms of dentine hypersensitivity by virtue of their remineralization potential [28-30].

6.3 Cercon – smart ceramics

It is based on a process that alloys direct machining of ceramic teeth and bridges. This allows bridges to be produced without stainless steel or metal. The zirconia based all ceramic material is created from one unit with no metal and without any baking. Thus producing an overall product which is metal free and biocompatible plus it also has the strength that helps resist crack formation.

Cercon delivers outstanding aesthetics without any compromise [8]. The zirconium oxide is a highly stable ceramic oxide typically used in areas where high strength and stability is required. The fracture toughness and flexural strength of zirconia are higher than alumina [31]. Thus the Cercon system offers a comprehensive solution to all prosthetic needs by taking advantage of strength, toughness, reliability and biocompatibility of zirconium oxide. The Cercon ceramics are also called smart as they are bio responsive [8].

7. Resin modified glass ionomer cement

Fluoride release is the property that grants GIC its smart status. The smart behavior of GIC is a good solution for caries prevention due to the salt phases present and also the long term fluoride release, recharge and re-release.The smart behavior of GIC is by mimicking the behavior of human dentine where the dimensional change is characterized by the coefficient of thermal expansion [32]. Under wet conditions the material is heated or cooled between 20°-50°C on cooling this process is reversed [33]. This behavior is similar to human dentine where very minute dimensional change is observed upon heating under wet conditions while a marked contraction is observed under dry conditions [33]. The smart behavior is also linked to the water content and how the material reacts to difference in water content within the surroundings. The benefit of fluoride release has been a subject of great debate and research over the years. The mechanism can be divided broadly into initial burst followed by stabilization and then the recharge of fluoride. The initial burst is the highest amount of fluoride released from the filling within the first 24-48 hours followed by the continuation and stabilization of the long term fluoride release for over 6weeks and up to 1-2 years in vitro. The level of release of fluoride over time decreases exponentially but the smart behavior of materials containing GIC salt phases offers some long term protection. There is evidence that the fluoride which is released from the salt phases can be replaced when the material is exposed to solutions containing high fluoride concentrations such as toothpastes and mouthwashes. Thus the re-released fluoride after recharging is more important than the initial burst of fluoride release which begins soon after setting of the material. Some research has also shown that fluoride release is temperature sensitive and more fluoride is recharged by use of warm fluoride solutions and this can generate more sustained release at mouth temperature. Another aspect exhibiting smartness of the material is prevention of demineralization around orthodontic brackets. At the same time mechanical properties are adequate for retention of the bracket yet the enable easy debonding at the end of treatment.

8. Smart Impression Materials

These materials are more hydrophilic and provide void free impressions. They have shape memory which allows elastic recovery and prevents distortion for accurate impressions. They have high flow and low viscosity allowing for higher accuracy [34].

9. Smart Burs

Smart prep burs are polymer burs which only removes infected caries; it leaves behind the intact dentine which has the capacity to regenerate and re mineralize. However the time required for caries removal is slightly higher [35, 36].

10. Smart fibers for laser dentistry

Laser is a type of electromagnetic wave generation [37]. The emitted laser has three characteristic features [38]:

- **Monochromatic:** the waves generated have the same energy and frequency.
- **Coherence:** waves generated are in the same phase and are related to each other in terms of speed and time.
- **Collimated:** the waves produced are almost parallel and the level of divergence is very minute [39]

Laser radiation is delivered by photonic fibers also known as 'smart fibers'. These are hollow cored photonic fibers (PCFs) [4].They are termed smart as they can ablate tooth enamel being developed [40]. The crystal fibers can be used for detection and optical diagnosis through plasma emission [40].

Smart materials by design:

Materials that contain a poly salt matrix can be designed to include and exhibit smart behavior by utilizing the following

- **Function of water:**

Smart behavior can be correlated to the ability of a structure to absorb or release solvent rapidly in response to a thermal stimulus. Depending on the nature of water and the strength of the bonds present, the dimensional stability of the structure may be enhanced or decreased [41].

- **Thermal behavior:**

Mostly the thermal behavior of any material is mainly dependent on its coefficient of thermal expansion. The problem with most dental materials is the discrepancy in their coefficients of thermal expansion as compared to the tooth therefore the materials tend to expand and contract to a greater extent than the natural tooth.

- **Expansion and radial pressure:**

By incorporating resins within the salt and gel matrix of the material the durability and longevity can be stabilized.

- **Biofilms and smart behavior:**

The presence of biofilm on the surface of a material alters the interaction of the surface with the environment and may act as a lubricant which prevents abrasive wear .The formation of biofilms and how they change the interaction of the material with the environment can affect the property of a material to great extent. It seems that biofilms can protect the surface from abrasive forces, initiation of caries and also concentrate fluoride. If the above mentioned properties can be integrated into materials and smart materials can actually be designed care should be taken so as not to neglect the requirements and original properties of the materials. According to Friend 1996‘the development of true smart materials at the atomic scale is still some way off, although the enabling technologies are under development. These require novel aspects of nanotechnology and the newly developing science of shape chemistry. Further need is to harvest this knowledge into designing a material which not only has a controlled design and structure but also fulfils the requirements of longevity and balanced smart interactions.

11. Potential benefits

The potential future benefits of smart materials, structure and systems are amazing. The technology promises optimum responses to highly complex problems by providing enhancements to many products it could provide better control by minimizing distortion and increasing precision. It could also enhance preventive maintaince of systems and thus improve their performance.

12. Conclusion

Currently the most promising technologies for lifetime efficiency and improved reliability include the use of smart materials and structures. Understanding and controlling the composition and microstructure of any new material is the ultimate objective of research in any field and is vital in production of future smart materials. The insight gained from studies of materials, their behavior, properties, reaction of molecules as they cool down or heat up. The change in structure as they deform or distort will speed up the development of new materials for use and definitely change the face of dental materials as we know. Further advancements in the field are not only required they are the need of the hour to compete with the ever changing and developing needs of dentistry.

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