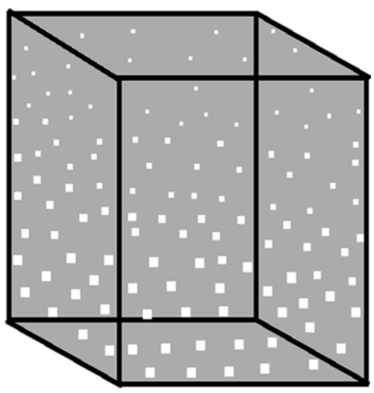
Functionally Graded Materials (FGMs) :

may be characterized by the variation in composition and structure gradually over volume, resulting in corresponding changes in the properties of the material. The materials can be designed for specific function and applications. Various approaches based on the bulk (particulate processing), preform processing, layer processing and melt processing are used to fabricate the functionally graded materials.

Types of Functionally Graded Materials

At the inception of the development of the functionally graded materials, the concept was to remove the sharp interface that existed in the traditional composite material, and to replace it with the gradually changing interface, which was translated into the changing chemical composition of this composite at this interface region.

The porosity gradient functionally graded material is another type of FGM, in which the porosity in the material is made to change with the change in the spatial position in the bulk material. The shape and size of the pore are designed and varied, according to the required properties of the Functionally graded material.



1- Compositional gradient FGM , 2- Microstructural gradient FGM and 3- porosity gradient FGM

Fabrication Techniques of FGM

The fabrication process is one of the most important fields in FGM research. A large part of the research work on FGMs has been dedicated to processing and a large variety of production methods have been developed for the processing of FGM. Most of the processes for FGM production are based on a variation of conventional processing methods which are already well established. Methods that are capable of accommodating a gradation step include powder metallurgy sheet lamination, and chemical vapor deposition and coating processes. In general, the forming methods used include centrifugal casting ,slip casting, tape casting , and thermal spraying . Which of these production methods is most suitable depends mainly on the material combination, type of transition function required, and geometry of the desired component.

It is noted that powder metallurgy method is one of the most commonly employed techniques due to its wide range control on composition and microstructure and shape forming capability. Powder metallurgy offers more advantages by means of the lower costs, higher raw materials availability, simpler processing equipment, lower energy consumption and shorter processing times.

Areas of Application of Functionally Graded Materials:

The important characteristics of the FGM have made them to be favoured in almost all the human areas of endeavour. Functionally graded materials are currently being applied in a number of industries, with a huge potential to be used in other applications in the future.

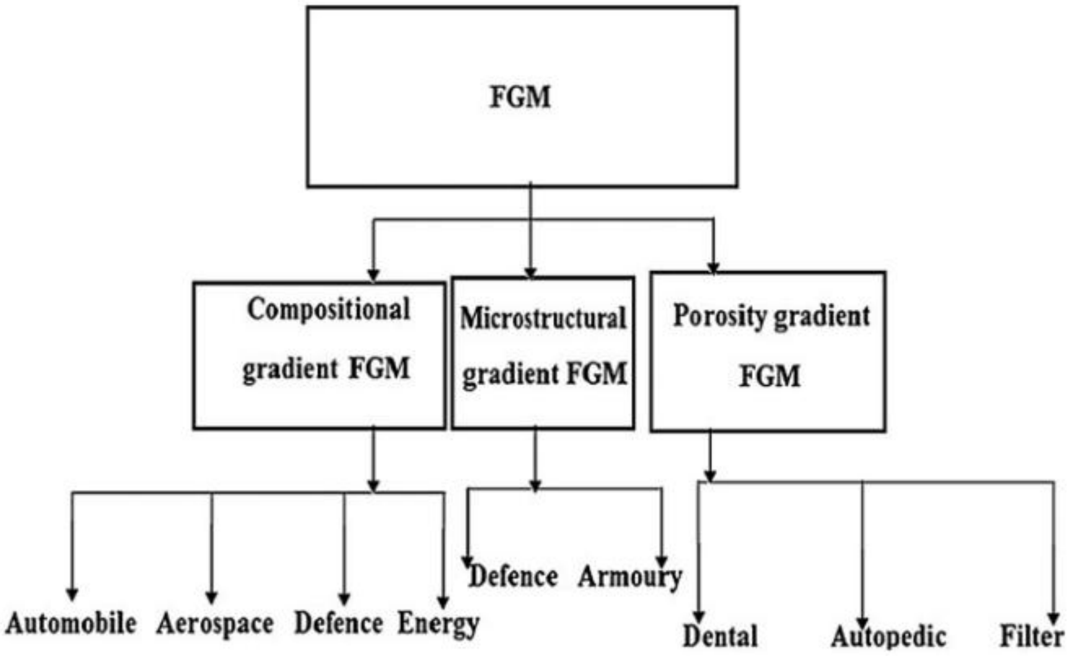


Figure Areas of applications for the three types of functionally graded materials

The Aerospace Industry

The initial application where functionally graded materials were developed was for space plane bodies. The application of this novel material is increased over the years in the aerospace industry. Most aerospace equipment and structures are now made of functionally graded materials. These include the rocket engine components, the spacecraft truss structure, the heat exchange panels, and some structures, such as the reflectors, the solar panels, the camera housing, the turbine wheels, the turbine blade coatings, the nose caps, the leading edge of missiles, and space shuttles. Functionally graded materials are also used for the structural walls that combine thermal and sound insulation properties.

The Automobile Industry

The use of functionally graded materials in the automobile industry is still limited at the moment, because of the high cost of production of functionally graded materials. However, the material is being used in very important parts of the automobile, where the present high cost justifies its use. The present applications include the engine cylinder liners for diesel engine pistons, for the leaf springs, for the spark plugs, the combustion chambers, the drive shafts, the shock absorbers, the flywheels, some car body parts, the window glass, and racing car brakes. Also, functionally graded materials are used in enhanced body coatings for cars, and that includes the graded coatings with particles, such as dioxide/mica.

Biomedical

The human body is made up of a number of functionally graded materials, which includes the bones and the teeth. These are the most replaced human body parts, as a result of damage to these parts, or as a result of the natural ageing process. The engineering materials that are biocompatible are used for their replacements. The natural parts that these materials replace are functionally graded materials in nature. This is why the majority of functionally graded materials used in the biomedical industry are used for implants. The porosity gradient functionally graded materials are most commonly used in this industry, because their properties are very close to those of the parts they intend to replace. Examples of where the porosity gradient FGM is used in the biomedical industry include the following: In the permanent skeletal replacement implants, graded porosity helps to minimize the stress shielding

Defence

The ability of the FGM to offer penetration-resistant properties by inhibiting crack propagation is an attractive property that makes the material favoured in the defence industry. The functionally graded materials are used in the defence industry in applications, such as bullet-proof vests, the traditional Japanese sword, and in armour plates . Another key area of application of functionally graded materials is in the body of bullet-proof vehicles.

Smart materials are designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields.

There are a number of types of smart material, some of which are already common. Some examples are as following:

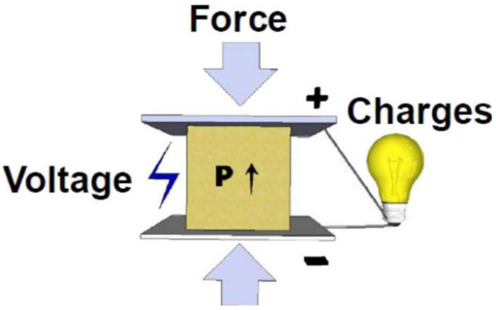
1. Piezoelectric materials are materials that produce a voltage when stress is applied. Since this effect also applies in the reverse manner, a voltage across the sample will produce stress within the sample. Suitably designed structures made from these materials can therefore be made that bend, expand or contract when a voltage is applied.
2. Shape-memory alloys and shape-memory polymers are materials in which large deformation can be induced and recovered through temperature changes or stress changes (pseudoelasticity). The shape memory effect results due to respectively martensitic phase change and induced elasticity at higher temperatures.
3. Magnetic shape memory alloys are materials that change their shape in response to a significant change in the magnetic field.
4. pH-sensitive polymers are materials that change in volume when the pH of the surrounding medium changes.
5. Temperature-responsive polymers are materials which undergo changes upon temperature.
6. Halochromic materials are commonly used materials that change their colour as a result of changing acidity. One suggested application is for paints that can change colour to indicate corrosion in the metal underneath them.
7. Photomechanical materials change shape under exposure to light.
8. Polycaprolactone (polymorph) can be molded by immersion in hot water.
9. Self-healing materials have the intrinsic ability to repair damage due to normal usage, thus expanding the material's lifetime.

10. Dielectric elastomers (DEs) are smart material systems which produce large strains (up to 300%) under the influence of an external electric field.
11. Thermoelectric materials are used to build devices that convert temperature differences into electricity and vice versa.

1- Piezoelectricity : is the electric charge that accumulates in certain solid materials (such as crystals, certain ceramics,) in response to applied mechanical stress. The word *piezoelectricity* means electricity resulting from pressure.

The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry. The piezoelectric effect is a reversible process in that materials exhibiting the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electrical field). For example, lead zirconate titanate crystals will generate measurable piezoelectricity when their static structure is deformed by about 0.1% of the original dimension. Conversely, those same crystals will change about 0.1% of their static dimension when an external electric field is applied to the material. The inverse piezoelectric effect is used in the production of ultrasonic sound waves.

The nature of the piezoelectric effect is closely related to the occurrence of electric dipole moments in solids. The latter may either be induced for ions on crystal lattice sites with asymmetric charge surroundings (as in $BaTiO_3$ and PZTs)



Materials of piezoelectric

Many materials, both natural and synthetic, exhibit piezoelectricity:

Naturally occurring crystals

- Quartz
- Berlinite ($AlPO_4$),
- Rochelle salt
- Topaz
- Tourmaline-group minerals
- Lead titanate ($PbTiO_3$). Although it occurs in nature as mineral macedonite, it is synthesized for research and applications.

The action of piezoelectricity in Topaz can probably be attributed to ordering of the (F,OH) in its lattice, which is otherwise centrosymmetric: orthorhombic bipyramidal (mmm). Topaz has anomalous optical properties which are attributed to such ordering.

Natural materials

- Silk
- Wood due to piezoelectric texture

Synthetic crystals

- Lithium niobate ($LiNbO_3$)
- Lithium tantalate ($LiTaO_3$)

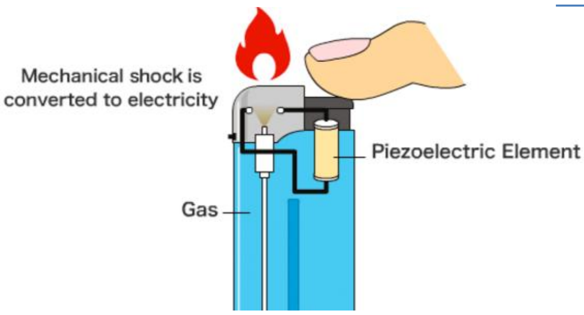
Synthetic ceramics

Polymers

- Polyvinylidene fluoride (PVDF): PVDF exhibits piezoelectricity several times greater than quartz.

Application of piezoelectric materials :

1- **High voltage and power sources (** cigarette lighter**)**



2-Sensors : The principle of operation of a piezoelectric sensor is that a physical dimension, transformed into a force, acts on two opposing faces of the sensing element. Depending on the design of a sensor, different "modes" to load the piezoelectric element can be used: longitudinal, transversal and shear.

2- **Actuators : such as AFM (Atomic force microscopes)**

3- Reduction of vibrations and noise

4- Surgery

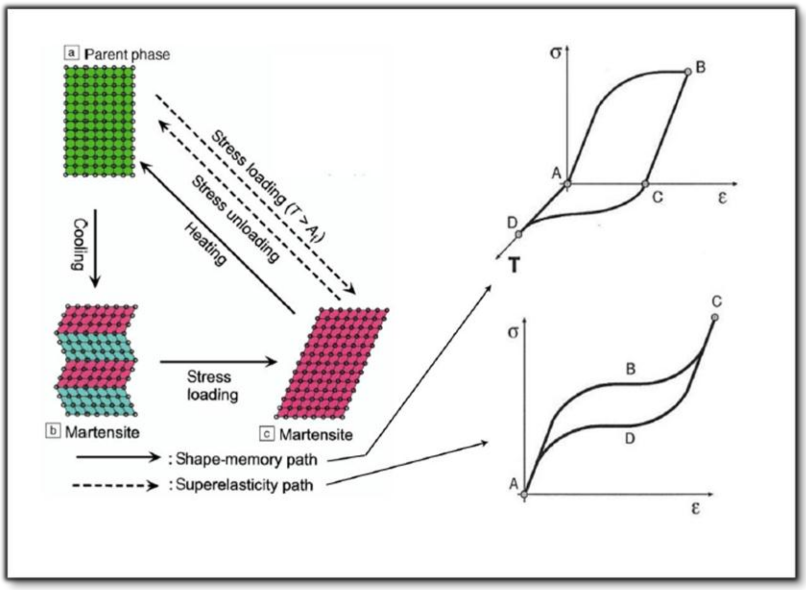
A recent application of piezoelectric ultrasound sources is piezoelectric surgery, also known as piezosurgery. Piezosurgery is a minimally invasive technique that aims to cut a target tissue with little damage to neighboring tissues.

H.W What is application of **piezoelectric** in biomaterials ?

2- Shape memory alloys (SMA)

Shape memory alloys (SMAs) are the most important branch of smart or intelligence materials, it's a metallic alloys which undergo solid-to-solid phase transformations induced at appropriate temperature or stress changes and during which they can recover seemingly permanent strains. The shape memory alloys were first observed in the 1930s, by Arne Olander while working with an alloy of gold and cadmium. This gold and cadmium alloy was plastically deformed when cooled but returned to its original configuration when heated.

Shape memory alloys have two phases namely austenite and martensite; Austenite is the high temperature or “parent” phase and exhibits a (cubic) crystalline structure while martensite is the low temperature phase that exhibits a crystalline structure . The transformation from austenite to martensite may lead to twinned martensite in the absence of internal and external stresses or detwinned martensite if such stresses exist at a sufficient level.



Materials

A variety of alloys exhibit the shape-memory effect. Alloying constituents can be adjusted to control the transformation temperatures of the SMA. Some common systems include the following (by no means an exhaustive list):

- Ag-Cd 44/49
- Au-Cd 46.5/50
- Cu-Zn 38.5/41.5 wt.% Zn
- Mn-Cu 5/35 at% Cu
- Fe-Mn-Si
- Co-Ni-Ga
- Ni-Fe-Ga
- Ti-Nb
- Ni-Ti

Application of shape memory alloy :

1- Aircraft and spacecraft

2- Automotive

3- Robotics

4- Civil Structures

5- Telecommunication

6- Medicine