

Analysis of Tribological Applications of Functionally Graded Materials in Mobility Engineering

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ABSTRACT

A functionally graded material (FGM) is a two component composite characterised by a compositional gradient from one component to other. In a traditional composite, which is basically a homogeneous mixture of its constituents the pure identity of each constituent is altogether lost and thus we have to make a compromise between the desirable properties of the constituent materials and our requirement. Most of the mechanical failures in the world are a result of one or the other modes of wear failure, especially in most of the mobility engineering applications. In this paper the various aspects of wear failures are discussed in the different modes of transport and a preventive measure is suggested by applying FGMs.

1. INTRODUCTION

In the days of smart materials, functionally graded materials are fast gaining popularity. These materials are a combination of two different types of material layers with a graded interlayer. These materials exhibit the characteristics of each individual material plus the new functionality. A functionally graded material (FGM) is a two component composite characterised by a compositional gradient from one component to other. In a traditional composite, which is basically a homogeneous mixture of its constituents the pure identity of each constituent is altogether lost and thus we have to make a compromise between the desirable properties of the constituent materials and our requirement. Since significant proportions of an FGM contain the pure form of each component, the need for compromise is eliminated. The properties of both components can be fully utilised. For example, the ductility of a metal can be mated with the refractoriness of a ceramic, without any compromise in the ductility of the metal or the refractoriness of the ceramic. Functional grading, can, also, be defined as the selective and reproducible adjustment of the microstructure of a material to the setting of macroscopic component properties (eg. Hardness, strength). The procedure during the development of the FGMs is a continuous change of the microstructure at least by one spatial dimension. During the development process, the properties keep changing at every step, till the target is achieved. The concept of FGM was developed in Japan in 1984 during a space craft research project. Where a combination of materials used would serve the purpose of a thermal barrier capable of withstanding a

surface temperature of 2000 K and a temperature gradient of 1000 k across a 10 mm section[1]. However since then this concept has gained international popularity, especially in Germany which is famous for its technological advancements. A trans-regional collaborative research centre (SFB Transregio) was established in 2006 in Germany in order to exploit the potential of grading mono-materials, such as steel, aluminium and polypropylene, by using thermo-mechanically coupled manufacturing processes. It is funded by the German Research Foundation.

However the concept of FGMs is present in nature in the form of the human bone and cellulose. Human Bone is a mix of collagen (ductile protein polymer) and hydroxyapatite (brittle calcium phosphate ceramic). The yellow marrow consists of fat which contributes to the weight and the red marrow is where the formation of red blood cells occur. A gradual increase in the pore distribution from the interior to the surface can pass on properties such as shock resistance, thermal insulation, catalytic efficiency, and the relaxation of the thermal stress. The distribution of the porosity affects the tensile strength and the Young's modulus. The human bone has high strength at the surface as it gradually lowers toward the inside by altering the porosity. From an engineering perspective, the human bone is a remarkable material having unique material properties that has the ability to repair itself and to adapt to its mechanical environment

The basic building unit of FGMs are elements or ingredients denoted by **maxel**. The term maxel was introduced Rajeev Dwivedi and Radovan Kovacevic at Research Center for Advanced Manufacturing (RCAM) in 2005.[3] The attributes of maxel include the location and volume fraction of individual material components. A maxel is also used in the context of the additive manufacturing processes (such as stereo-lithography, selective laser sintering, fused deposition modelling, etc.) to describe a physical voxel (a portmanteau of the words 'volume' and 'pixel'), which defines the build resolution of either a rapid prototyping or rapid manufacturing process, or the resolution of a design produced by such fabrication means. The materials can be designed for specific functions and applications. The properties that may be designed/ controlled for desired functionality include chemical, mechanical, thermal, and electrical properties.

Depending upon the nature of gradient and microstructure , the FGMs may be classified as[1].

- 1) Fraction gradient type (Fig. 1a)
- 2) Shape gradient type (Fig.1b)
- 3) Orientation gradient type (Fig.1c)

4) Size (of material) gradient type (Fig.1d)

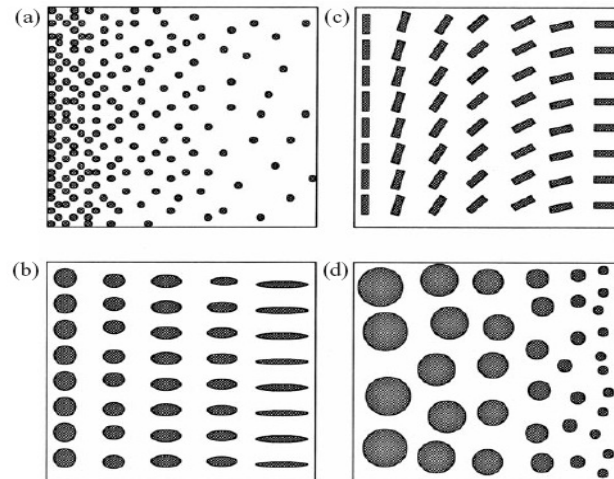


Figure 1. Gradation of FGMs (a) volume fraction, (b) shape, (c) orientation and (d) size [14].

There are various techniques by which FGMs can be manufactured depending upon the cost savings and expediency. The most popular is Powder Metallurgy others are powder stacking, plasma spraying, slip casting, electrophoretic deposition and sedimentation etc.

2. Tribology and Functionally Graded Materials

Tribology is the science dealing with friction wear and lubrication of contacting machine elements in contact. Most of the mechanical failures in the world are due to wear of machine parts either due to improper lubrication or due to adverse working environment. Some other factors responsible for tribology related failures are:

- High Loads, Speeds or Temperature
- Improper Lubrication
- Misalignment
- Mishandling
- No break in
- Lack of anti scuff additives
- Improper Maintenance

The different modes of tribological failures, specially seen in mobility applications can be due to:

- I. **Abrasion:** One contacting body abrades the other or there can be a third body present between the bodies in contact. For example, abrasive wear at the lower turning point of the piston rings in cylinder liners can be observed (Figure 2.1). The second cylinder liner has been damaged by piston seizure. This kind of damage is typically caused by hard particles (e.g., sand dust) and deposits on the piston crown.

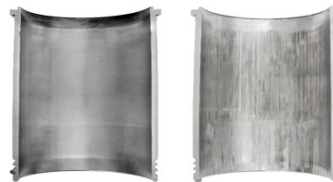


Figure: 2.1 Cylinder Liner before and after wear.

- II. **Adhesion:** During relative motion between the two bodies in contact, parts of the softer body can break and adhere to the harder body, thus creating pits and parallel furrows. For example adhesive wear in the bearing (Figure 2.2) occurs when intimate contact is made over a number of small patches or junctions. During sliding, these junctions continue to be made and broken, and, if a junction does not break along the original interface, a wear particle is formed. These particles eventually break away, causing pitting and spalling.

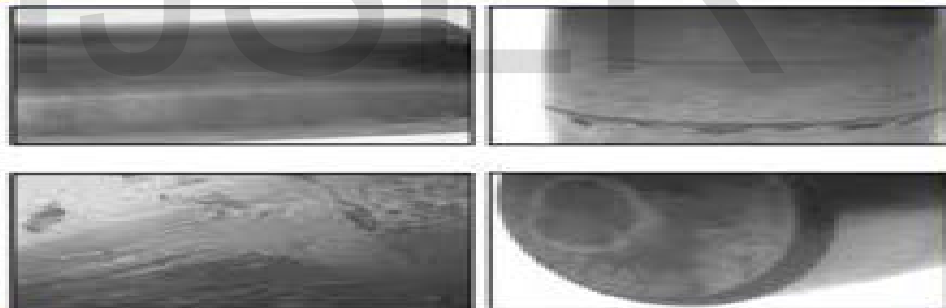


Figure: 2.2 Automotive Bearing before and after wear.

- III. **Fatigue:** Due to the above two modes of wear or due to the presence of stress concentration points as a result of manufacturing procedures, mishandling or environmental adversities cracks can develop leading to fatigue failure. For example fatigue wear can be observed in the gear tooth (Figure 2.3). The metal removal by pitting, spalling and cracking can be observed due to cyclic loading during transmission of power.

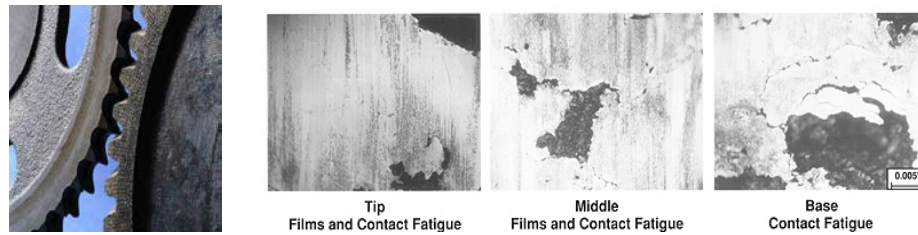


Fig 2.3 Gear Tooth before and after Fatigue Wear

IV. **Corrosion:** is the material removal or loss by oxidative chemical reaction of the metal surface in the presence of moisture. It can further be either

- Frictional corrosion is a general form of wear caused by loaded micro-movements or vibration between contacting parts without any water contaminant being present, although humidity may be necessary. It may also be referred to as fretting wear.
- Fretting corrosion is the mechanical fretting wear damage of surface asperities accompanied and escalated by corrosion, mostly oxidation in air with some humidity present. It occurs due to many oscillating micro-movements at contacting interfaces between loaded and mating parts in an unlubricated contact.

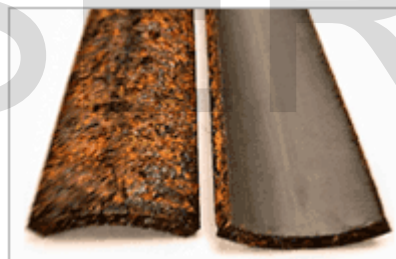


Figure 2.4 Fretting Corrosive wear in pipings

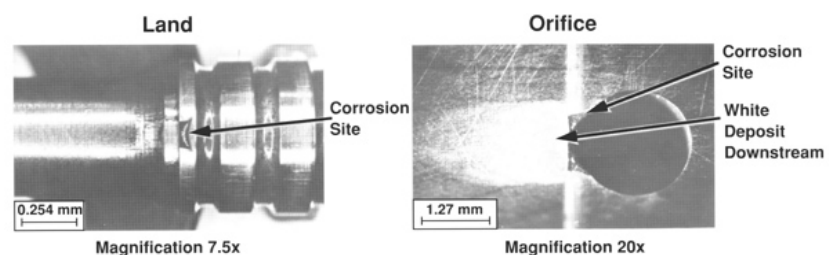
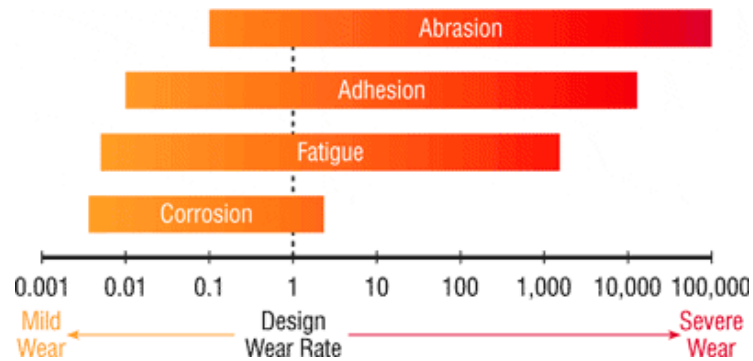


Figure 2.4.1 Electro-corrosive Wear on Aircraft Servomechanism valve

The high velocity liquid flow, stray currents and the galvanic metal combinations cause electro-corrosive wear on the aircraft servomechanism valve, Fig 2.4.1 appearing as corrosion pits.

Apart from these modes there are many other modes of wear such as erosive wear, percussive wear, electric wear etc, which are secondary to the above modes. During the tribological failure of a component, the mode of wear at the initial stage changes or transforms to another mode in the final stage.



**Figure 2.5 Normalized Wear Rates for Industrial Machinery
(Wear Volume/Distance) x (Hardness/Load)[9]**

In Figure 2.5, the term “design wear rate” has a value of 1 for the conditions that will achieve the manufacturer’s projections for machine life. Industrial machinery is designed to survive about 40,000 hours mean time between failures (MTBF). Increasing or decreasing wear rates can result in far more or far less than 40,000 hours MTBF. Some wear prone mechanical elements in mobility applications are:

- **Automobiles:** Valves, Piston rings, Cylinder Linings, Gears, Cylinder Lifter, Bearings, Gears, Seals, shafts, Chain drives etc.
- **Aerospace:** Rocket heat shields Rocket nozzle, Heat exchange panels, Spacecraft truss structure, Reflectors, Solar panels, Camera housing, Turbine wheels etc.
- **Marine:** Most of the marine transport are powered by diesel engines that use inexpensive, high-sulfur fuel. However, their combustion products contain oxidized sulphur and water vapor. These combine to form sulfuric acid, which is highly corrosive to the cast iron cylinders and piston rings. This corrosion is effectively controlled by using highly alkaline-type cylinder lubricants that neutralize the acids.

Thus, about 90% of failures worldwide are due to one or the other kind of wear modes. This hinders in the productivity, functionality, efficiency and economical viability of the application[10]. FGMs offer great promise in applications, subjected to high wear and friction under adverse conditions.

2.1 Wear Resistant FGMs

A low-cost functionally graded material would be ideal for wear-resistant applications in automobiles, aerospace and water transport machinery. For

example in a ceramic metal combination such a material would comprise a hard ceramic face on the exposed side, a tough metal face on the rear side that can be bolted or welded to a support frame, and a graded composition from metal to ceramic in between. The gradation would enhance the toughness of the ceramic face and also prevent ceramic-metal debonding. Such a material would uniquely combine the following attributes:

- High Wear resistance (ceramic face)
- High Toughness (impact resistance)
- Easy joint ability: weldable/ boltable to metal supports

It would be pointless in developing such a material unless it could compete commercially with the wear-resistant ceramics currently in the market, with alumina at the bottom end and imported tungsten carbide at the top end of this range. Unless this can be achieved, the potential benefits of bulk wear-resistant tiles of metal-ceramic FGMs will remain an unrealised possibility.

3. TRIBOLOGICAL APPLICATIONS OF FGMs

Macro-scale FGMs offer a new method of surface engineering to produce tailored tribological properties. FGMs finds wide spectrum of utility in diverse areas such as electronics and communication, electrical, structural, biomedical, aerospace, automotive, defense, and general engineering[7]. Some of the wear resistant applications of functionally graded materials are highlighted below:

- **Mobility:** Functionally graded materials can withstand very high thermal gradient, this makes it suitable for use in structures and space plane body, rocket engine component etc [[8]. They are being used as cylinder linings, valves. Bearings. Gears etc. In marine transport also due to adverse environmental conditions they are being used as coatings.
- **Medicine & Biosciences :** Living tissues like bones and teeth are characterized as functionally graded material from nature [35], to replace these tissues, a compatible material is needed that will serve the purpose of the original bio-tissue. The ideal candidate for this application is functionally graded material. FGM has find wide range of application in dental [36] and orthopedic applications for teeth and bone replacement. The functional gradient nano hydroxyl apatite reinforced polyvinyl alcohol (nano HA/PVA) gel bio-composites can be prepared through a layer-by-layer casting method combining with freeze/thaw cycles technology. NanoHA/PVA gel biocomposites have been a promising and excellent artificial articular cartilage repair material. Compared to hydrogel-based materials such as poly(vinyl alcohol) (PVA), poly(lactic acid) and chitosan, nanoHA/PVA gel biocomposites possesses superior bioactivity and mechanical properties because of the nanoHA existence in the composites [4].

- **Defense:** One of the most important characteristics of functionally graded material is the ability to inhibit crack propagation. This property makes it useful in defense application, as a penetration resistant materials used for armour plates and bullet-proof vests [5].
- **Energy:** FGM have been used for various energy and sensor applications such as graded thermoelectrics and dielectrics (e.g. thin films prepared by chemical solution deposition), piezoelectrically graded materials, applied for broadband ultrasonic transducers, and graded composite electrodes for solid oxide fuel cells (SOFC). FGMs are also used in energy conversion devices. They also provide thermal barrier and are used as protective coating on turbine blades in gas turbine engine [1,2]
- **Optoelectronics:** FGM also finds its application in optoelectronics as graded refractive index materials and in audio-video discs magnetic storage media. They are used as tungsten–copper composites for high current connectors and diverter plates, electrodes for thermionics, photocatalysts, advanced superconducting wires, optical polymers, magnetic properties, liquid crystals, single crystals with tuned lattice constant for X-ray mono-chromators. Other areas of application are: cutting tool insert coating, automobile engine components, nuclear reactor components, turbine blade, heat exchanger, Tribology, sensors, fire retardant doors, etc [2-4].
- **Commercial and Industrial:** Pressure vessels, Fuel tanks, Cutting tool inserts, Laptop cases, Wind turbine blades, Fire fighting air bottles, MRI scanner cryogenic tubes, Eyeglass frames, Musical instruments, Drilling motor shaft, X-ray tables, Helmets.

The list is endless and more applications are springing up as the processing technology, cost of production and properties of FMG improve [10]

3.1 FGMs in Mobility Engineering Applications

As FGMs are a class of composites that have continuous variation of material properties from one surface to another and thus alleviating the stress concentration found in laminated composites. The gradation in properties of the material reduces thermal stresses, residual stresses, and stress concentrations" [7]. The most exciting realization of FGMs, that gradients can be designed at a micro structural level to tailor specific materials for their functional performance in particular applications is being utilized in the following applications, replacing traditional composites and pure metals.

- **Automobiles & Railways:** Some of the applications are
 - ✓ (SiC-SiC) Combustion chambers,(AlSiC) Engine cylinder liners, (SiCw/Al-alloy) Diesel engine pistons, (E-glass/epoxy) Leaf springs, (Al-C) Drive shafts, (Al-SiC) Flywheels,
 - ✓ Racing car brakes, (SiCp/Al-alloy)
 - ✓ Crank shaft
 - ✓ Shock absorbers disc brakes and clutches,
 - ✓ vehicle support surface.

- ✓ Anti Corrosive Coatings
 - ✓ Railway axle, wheels, rail tracks, bulletproof glass. Engine parts
 - ✓ Railway carriages of high speed trains
 - ✓ Joints with high strength and toughness for railways
- **Aerospace & Aircraft structures:** Some of the applications are
 - ✓ (TiAl-SiC fibers) Rocket nozzle, Heat exchange panels, Spacecraft truss structure, Reflectors, Solar panels, Camera housing, Turbine wheels (operating above 40,000 rpm), Nose caps and leading edge of missiles and Space shuttle.
 - ✓ An FGM made of ceramic and metal can provide the thermal protection and load carrying capability in one material thus eliminating the problem of cracked tiles found on the Space Shuttle [15].
 - ✓ Aircraft runways
 - ✓ Fuselage and wings using a spar comprising a web and a flange extending laterally from the web, the structure comprising a plurality of plies of fibre-reinforced composite material.
 - ✓ Helicopter landing gear includes a pair of skids; and one or more cross members extending between the pair of skids made of fiber-reinforced, organic matrix, composite structural member includes a plurality of layers of fiber-reinforced, organic matrix, composite material.
 - ✓ Noise Reduction Sensors.
 - ✓ FGM of carbon and nitrogen in tungsten or a tungsten alloy for coatings in aeronautical applications
 - ✓ An aerospace vehicle comprising a plurality of composite stiffeners, each stiffener of the plurality having a stack of plies of reinforcing fibers used in space travel.
 - ✓ Stringers for aircrafts (carbon fiber reinforced plastics)
 - **Marine, Navy and Ship Building:**
 - ✓ Propulsion shaft (Carbon and glass fibers),
 - ✓ Cylindrical pressure hull (Graphite/Epoxy),
 - ✓ Sonar domes (Glass/Epoxy)
 - ✓ Composite piping system, (Al-SiC) diving cylinders [13]. Armor panel system to deflect incoming projectiles (tungsten carbide, E-Glass).
 - ✓ Detection sensors
 - ✓ Wear resistant coatings having solid particles of a laser-treated T6V titanium alloy as one component of FGM.
 - ✓ Submarine parts and outer fuselage

4. CONCLUSION

The friction and wear behaviours of components used in various mobility engineering applications are very complex because of variable speeds and loads, dissipation of energy and temperature rise. Among the conclusions derived from the above analysis the foremost is the that most of the catastrophes of machine failure can be avoided by fabricating FGMs as per the requirement of the application and proper condition monitoring. FGM are becoming one of the potential advanced materials for most of the tribological applications. Since the FGMs are produced to achieve a certain property requirement in particular positions of a component, it is better to work out an inverse design in developing the functionally gradient materials for the specific application or component. There is vast potential for the development of new functionally graded composites as well as new processing methods.

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