



# Functionally Graded Materials beyond Conventional Design: Multiscale Modeling, Advanced Manufacturing, and Emerging Engineering Applications

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## ABSTRACT

Functionally graded materials (FGMs) are a new generation of superior materials that default compositions, microstructure, and functions with smooth changes in volume within a material. The paper is a thorough review of the history of FGMs since the 1980s when it was first developed in Japan, until now where it has seen a wide variety of uses in aerospace, biomedical and energy industries. The theoretical considerations of the design of FEM are systematically discussed in the paper the composition variability, optimization of the gradient, and mechanical and thermal behavior analysis. A special emphasis is laid on the functional graded additive manufacturing (FGAM) technology, which focuses on the optimization of procedures of the techniques, i.e. selective laser melting, fused deposition modeling, and the new multi-material additive manufacturing technology. Significant applications to engineering examined by the review are lightweight aerospace components, which have better thermal management, orthopedic implants, which have better integration and reduced stress shielding, and energy systems, which include new thermal barrier coating. In spite of the significant advances, the extensive industrial implementation of FGMs are still burdened by the challenges such as the excessive costs of production, the technical restrictions connected with defect control and standardization of quality products, and the inexistence of the regulatory frameworks. The paper ends with the definition of the future research directions, which include the use of artificial intelligence and machine learning in predictive design, the introduction of nanocomposite-enhanced FGMs, and convergence with smart technologies to monitor and adapt to real-time. These developments make FGMs become a key facilitator of sustainable, high-performance engineering solutions to the next-generation applications.

## 1. Introduction

### 1.1. Definition and Characteristics of FGMs and FGSs


Functionally graded materials (FGMs) are high-technology materials that are developed with functions progressively varying in their volume. This gradual change enhances

mechanical, thermal and electrical performance in most areas of engineering. FGMs are characterized by series of stages that are organized in continuous, succession, and a change in structure or composition can be achieved according to particular requirements.

Among the major benefits of FGMs lies the fact that, they will minimize the stress

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concentration levels which are typical of conventional layered materials. These materials do not have sharp transitions and instead they spread the stress force uniformly. This is particularly when dealing with aerospace components that are prone to severe environments and biomedical implants that need to blend with tissues naturally.

FGMs were created to overcome the drawbacks of the traditional homogeneous material and composites. Japanese researchers started to investigate graded materials capable of keeping high temperatures and being strong in 1980s. Since, development of powder metallurgy and additive manufacturing have made it possible to control material placement and complicated shapes with much precision.

The materials provided have a multifunctional use specific to their purposes. FGMs in aerospace develop lightweight structures, which are resistant to heat and which can withstand varying loads. In healthcare, they offer mechanical characteristics that more closely approximate natural tissue that enhance

implant fitment and minimize typical problems with the equipment.

The characteristics microstructures such as grain size and phase distribution have a considerable impact on the response of FGM to stress. Differentiations in heat flow are also handled by thermal conductivity gradients that allow differences in expansion without causing dimensional instability.

The production of FGMs needs to be dedicated to development and manufacture. Additive manufacturing is enhancing flexibility and accuracy but there are challenges that include the optimization of processes and control of defects before mass production is rife. In general, FGMs merge personalized properties and inter-functionality, widening the usage in most engineering fields, [1], [2], [3], [4]. The following table 1 summarizes the fundamental characteristics, benefits, and applications of Functionally Graded Materials (FGMs) and Structures (FGSs). Moreover, table 2 below compares FGMs with conventional composite structures.

**Table 1.** Overview of Functionally Graded Materials (FGMs).

Category	Description
<b>Core Definition</b>	High-technology materials where composition, structure, and functions change progressively throughout the volume.
<b>Key Characteristics</b>	Continuous succession of stages; gradual transitions instead of sharp interfaces; tailored thermal/mechanical/electrical gradients.
<b>Primary Advantage</b>	<b>Minimization of stress concentration:</b> By removing sharp boundaries found in traditional laminates, they spread forces uniformly.
<b>Historical Origin</b>	Developed in the 1980s by Japanese researchers to create materials capable of withstanding extreme temperature gradients.
<b>Manufacturing Drivers</b>	Advanced via powder metallurgy and <b>Additive Manufacturing</b> , allowing for high-precision material placement and complex geometries.
<b>Strategic Benefits</b>	Reduced stress shielding (biomedical), enhanced thermal management (aerospace), and dimensional stability under heat flow.

**Table 2.** Key Comparison: Traditional vs. Functionally Graded Materials.

Feature	Traditional Layered Composites	Functionally Graded Materials (FGMs)
<b>Interface</b>	Discrete, sharp boundaries between materials.	Continuous, smooth gradient transition.
<b>Stress Distribution</b>	High stress concentration at interfaces (delamination risk).	Uniform stress distribution across the volume.
<b>Failure Modes</b>	Prone to cracking or peeling at the bond line.	Highly resistant to interfacial failure and thermal shock.
<b>Thermal Response</b>	Expansion mismatch often leads to warping.	Gradual thermal conductivity limits dimensional instability.
<b>Design Philosophy</b>	One-size-fits-all homogeneity.	"Material by design" — tailored for specific local requirements.

### 1.2. Historical Context and Development

At the end of the 1980s, the new type of new materials known as functionally graded materials (FGMs) came about in response to the shortcomings of uniform materials. Initial studies revealed that improvements in performance can be gained through gradually altered material properties particularly in the demanding areas such as the aerospace and biomedical sectors. Japanese researchers invented FGMs to resist sudden rises in temperature that was handy in thermal resistant barriers as well as components of aerospace.

The creation of FGMs was heavily connected with the progress in production. Powder metallurgy was tried first though it had difficulty in producing smooth gradients. Additive manufacturing methods like laser sintering and 3D printing later gave shorter control over the distribution of materials and enable engineers to create intricate shapes with a customized behavior.

The most common research has been carried out on mechanical and thermal performance. The better analytical methods and simulations demonstrated that compositional gradients reduce the concentration of stress and enhances the dimensional stability in a variety of

conditions. The insights help in developing FGMs that will be more effective in adverse conditions.

The aerospace is not the only area of interest about FGMs. Medically, they are used in the generation of scaffolds that would resemble natural tissues in aiding regenerative treatment and implants with a higher level of biocompatibility.

Although this may have some benefits, the implementation of FGMs in the industry has some challenges. The cost of manufacturing is also high and due to the fact that there are no uniform rules the companies are hesitant to change to a new material. Further adoption is inhibited by risk aversion.

In recent years, there has been an attempt to streamline the process of fabrication and demonstrate the costs benefits in the long term. By incorporating FGMs and intelligent technologies into each other, it will result in real-time operational controls and optimization to promote reliability and performance. On the whole, FGMs are the continuous development based on innovation and science, and researchers strive to increase their use in the sphere of engineering, [3], [5], [6] and [7].

Table 3 shows a structured summary of functionally graded materials evolution.

**Table 3.** The Evolution of FGMs: A Historical Timeline.

Period	Key Development	Primary Goal
Late 1980s	<b>The Japanese Initiative:</b> First conceptualized by researchers for spaceplane projects.	To create thermal barrier coatings that could survive extreme temperature drops (Ceramic-to-Metal).
1990s - 2000s	<b>Powder Metallurgy Era:</b> Initial fabrication using layered powders.	To transition from "step-wise" layers to smooth, continuous compositional gradients.
2010s - Present	<b>Additive Manufacturing (AM) Revolution:</b> Use of Laser Sintering and 3D printing.	To achieve precise control over complex 3D shapes and internal microstructures.
Future	<b>Smart Integration:</b> Combining FGMs with AI and real-time sensors.	To create "intelligent" structures capable of self-optimization and operational control.

**1.3. Importance of Tailored Multifunctional Properties**

The functionality of functionally graded materials (FGMs) is an excellent solution to the engineering field because they can be tailored to warrant multifunctional characteristics. They are designed to allow adaptation of composition, which is achieved over time with the built in capacity, to address certain mechanical, thermal, and electrical requirements, below section 2.1. With gradients designed with good care, designers can create materials that are exactly tailored to the stress and conditions that they will be working in. It is particularly relevant in the aerospace industry where temperature changes and mechanical forces can be dealt with directly to enhance safety and reliability.

The FGMs are also used to counter the pitfalls that are typical in normal materials such as the concentration of stress at the notch or cracks. Section 2.2 indicates how the response to stress can be changed based on variable microstructures and it distributes the stress more widely in a part. These materials, therefore, are stronger and can withstand long in tough environments and this reduces the cost of maintenance as well as downtime.

Functional grading designs can be used in the medical field to enable them to better match biological tissues. Using FGMs when fabricating orthopedic implants, tissue

engineering scaffolds etc., it is possible to closely replicate the mechanical properties of bones or other tissues in the body. This promotes rapid recovery and improved outcomes in patients preventing complications like stretch shielding which occur when using homogeneous materials.

The FGMs have also been integrally relevant in energy-driven applications where the flow of heat is a major concern. Thermal conductivity can also be modified in these materials by engineers in order to increase the efficiency of equipment such as solar panels and turbines. They also aid in controlling expansion variation that occurs with the change of temperature, and they maintain constant performance in changing conditions.

More to the point, the combinations of FGMs and smart technologies present some novel opportunities as section 6.2 will discuss. These combinations allow the real-time tracking of the inside structures to facilitate the predictive maintenance of the structures, which significantly enhances the operational efficiency across such industries as aerospace and healthcare.

Regardless of its obvious benefits, there are still a number of obstacles that cause FGMs to enter the mass production. Stereotypes of section 5.1 are technical issues that hamper adoption, and this section 5.2 brings cost to adoption. Nevertheless, current progress is

enhancing the process of production, particularly additive manufacturing that would be less costly to fabricate and could be used in more sectors of industry.

Lastly, the customized multi functionality of FGMs is also a factor in sustainability that offers the benefit of lighter designs without affecting the strength or performance. Such

attributes are essential in coming up with environmentally friendly solutions to meet the current industrial needs across the world, [3], [8], [9] and [10]. Figure 1 shows FGMs gradually change composition → properties change smoothly → stress, heat, and mechanical loads are better managed.

Aspect	Explanation	Example Applications	Engineering Benefit
Tailored Mechanical, Thermal, and Electrical Properties	FGMs allow gradual variation of material composition	Aerospace structural components	Improved reliability and safety
Stress Distribution and Crack Resistance	Reduces stress concentration at notches and cracks	Turbine blades, structural parts	Increased durability and service life
Biomedical Compatibility	Mimics mechanical properties of tissues	Orthopedic implants, tissue scaffolds	Reduced stress shielding
Thermal Management in Energy Systems	Better control of heat flow	Solar panels, turbines	Enhanced efficiency and stability
Integration with Smart Technologies	Embedded sensors for real-time monitoring	Aerospace monitoring, smart implants	Predictive maintenance
Sustainability and Lightweight Design	Weight reduction with strength maintained	Lightweight aircraft, renewable devices	Environmentally sustainable
Manufacturing Challenges	High complexity and costs of production	Additive manufacturing	Research to lower costs

**Figure 1.** Importance of Tailored Multifunctional Properties in FGMs.

Figure 2 show cellular co-continuous composites inspired by nature: (a) Nature-based composites comprise of rigid shells and cores made of soft materials; (b) How to build cellular co-continuous composites Nature has developed a geometry that separates the space into two interchangeable domains: it is the Gyroid surface that forms the basis of constructing cellular composites. The volume can be varied and the structure can be patterned and modified to have a shell-core structure (c) The 3D printing process is used to turn a computer-aided design (CAD) into an object of three-dimensional nature.

## 2. Theoretical Foundations of Functionally Graded Materials

### 2.1. Composition Variability and Gradient Design

FGMs have a composition and structure transition that is smooth, which enables the material to work in different properties. The

manipulation of mechanical, thermal, and electrical characteristics with regard to its individual requirements can be done by engineers with careful makeup. The process of selecting the materials is not only about their fundamental characteristics. The designers also have to look at the interaction and the bonding of these materials during the processing. Such parameters as strength, flexibility, heat conduction and wear resistance significantly contribute to the selection of parts that interact well down the gradient.

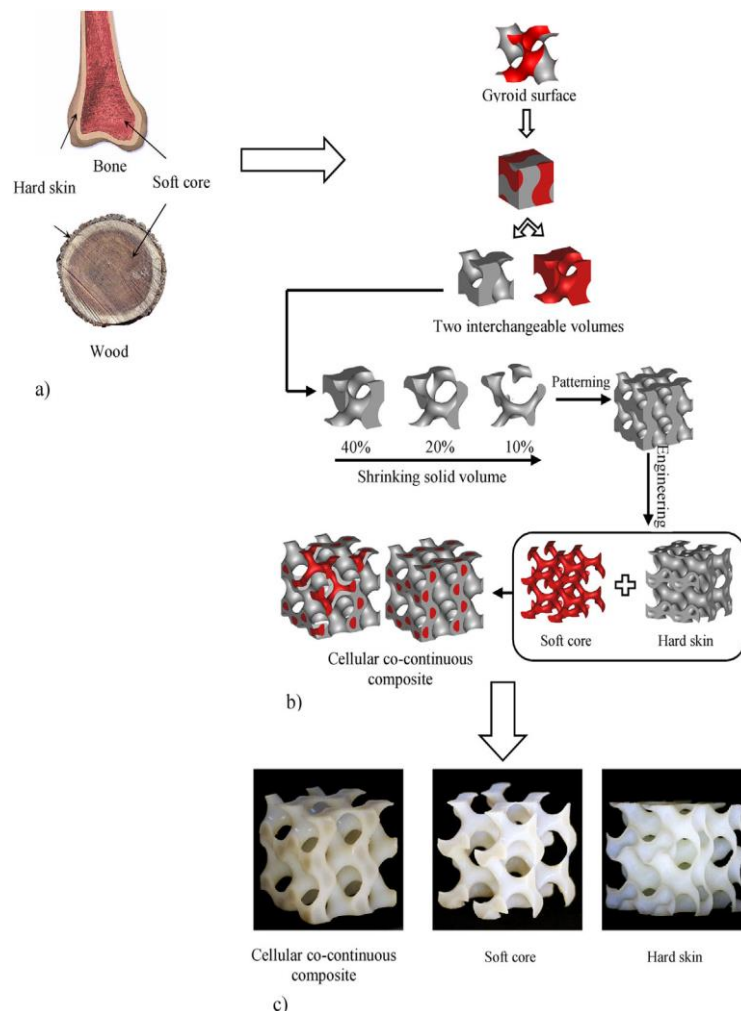
FGMs microstructure has a significant impact on their performance at varying conditions. The performances are influenced by the changes in grain size, phase arrangement and porosity. Considering the example of the smaller grains, which tend to enhance the strength without eliminating ductility due to the grain boundary effects. Also, the existence of gradients results in special microstructural regions, notably in

interfaces, and which are more advantageous in To develop practical gradients, one needs to have a clear understanding of the reaction of composition and microstructure to many forces. Engineers usually begin with specific property objectives, and they aim to either decrease or enhance some of the characteristics with regards to the purpose. It is a method that deeply depends on a process of sophisticated computer modeling to find out how various material structure will perform itself in advance to the actual production.

These complex gradients in actual parts demand manufacturing issues to be dealt with. Production techniques should be able to withstand the varying make-up without diluting

dealing with loads or eliminating thermal loads. the total form. Additive manufacturing is one of the emerging solutions, which provide a high level of control over the distribution of materials on various scales in a single element.

With functional grading, designers do not enhance specific properties in isolation anymore, designers introduce the benefits of multi-functionality. This is particularly useful in such an application as aerospace where reducing weight whilst still retaining superb thermal control could be the difference between success and failure in terms of performance and efficiency, [3], [5], [8], [11] and [12].



**Figure 2:** Cellular co-continuous composites inspired by nature, [8].

## **2.2. Mechanical and Thermal Properties Analysis**

Functionally graded materials (FGMs) are characterized by peculiar mechanical and thermal properties occurring because of the progressively varying microstructure. This difference gives FGMs more flexibility to fit mechanical loads and consequently can be used well where specific performance characteristics are required. In contrast to homogeneous materials, stress redistribution is more fluent throughout the structure of FGMs in view of their compositional gradient. As an illustration, when FGM has a different elastic modulus, it has the potential of alleviating common stress concentrations like those around cracks or notches. Profiling the gradient allows the designer to achieve much smoother gradient stress spikes without sacrificing the material strength.

According to experimental research, the grading exponent is influential in dispensing strength and deformation through FGMs under stress of various kinds. Although the benefit of a fixed elastic modulus is that this gives a uniform stress response, this is not necessarily the case in which the benefit of a fixed elastic modulus could reach optimum strength. Rather, when it comes to achieving consistent strength by assessing the material through grading it critically can be used to enhance the performance of the entire structure.

It is also significant to FGMs to have thermal behavior. The thermal conductivity of components is common designing, in order to produce desired temperature gradients within. They regulate the amount of heat flowing and the temperature dispersing during operation by replacing materials with good thermal conductivity with lower rates in the gradient. This property comes in handy in applications that experience rapid variations in temperature, or in applications that are exposed to intense heat.

In addition to this, research studies indicate that thermal expansion differs across FGMs since they are not uniformly organized. Various parts develop different rates of growth aided by heat thus dimensional stability and the duration of which a component varies with the extent of usage. Such changes of expansion rates have to be taken into consideration during design to make it durable. When mechanical and thermal considerations are combined, it shows that a careful gradient design results in tremendous savings compared to a conventional material. Continued studies are being done to find improved means of coping with stress and heat by coming up with innovative compositions. All in all, FGMs can be considered as providing universal solutions to engineering problems that need combination of hardness and temperature regulation, [1], [11] and [13], see figure 3.

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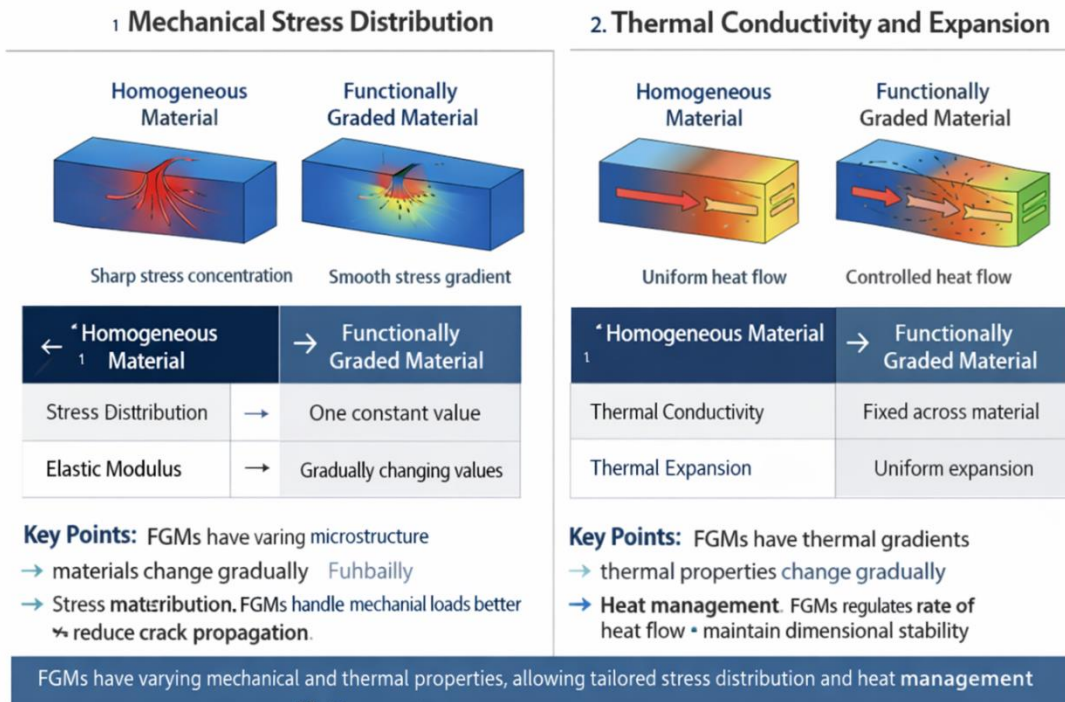


Figure 3. Mechanical and Thermal Properties Analysis of FGMs.

### 3. Fabrication Techniques for Functionally Graded Additive Manufacturing (FGAM)

#### 3.1. Overview of Additive Manufacturing Technologies

Functionally graded materials (FGMs) and structures (FGSs) have been changed through additive manufacturing (AM). It allows the fine manipulation of material composition and structure such that shaped elements can be complex and difficult to obtain via traditional technologies. FGMs can be built using AM methods; however, Fused Deposition Modeling (FDM) and Stereolithography (SLA) are of afforded significance in developing FGMs.

FDM is a technique that has been applied by adding a layer of thermoplastic using a heated nozzle. This method of building gradually gives an opportunity to combine various materials during a single print. It is possible to have gradients in the material properties by engineers altering filler content or changing the type of filament used during printing. This helps to generate parts with mechanical or thermal custom-designed characteristics.

SLA involves a photo reactive resin that hardens when exposed to ultraviolet light allowing it to have a better resolution and

enlisted finer details compared to FDM. It is superior in surfaces that are smooth and geometry with complex details like in the biomedical sector through synthetic scaffolds of tissues and specially designed implants.

Although positive, FDM and SLA have problems, which restrict their adoption by the industry. Processing parameters are hard to manage and could produce defects such as defective layer-to-layer warping or poor bonding. There is still need to gain a better insight on how processing influences the structure and properties in AM in FGMs.

Recent developments are aimed at maximizing print pace and quality of the materials. Other innovations such as multi-material printing enable depositing of various materials at the same time, which enhances the control of property distribution. Incorporating machine learning can also be used to predict the most profit-oriented process setups, rates of prototyping are also accelerated and time-to-market is minimized.

In summary, AM techniques such as FDM and SLA present emerging possibilities in designing functionally graded structures that would find useful applications in freedom in the aerospace, biomedical engineering and

energy system fields, [1], [2], [4], [13] and [14].

### **3.2. Process Optimization Strategies for FGAM**

Already, additive manufacturing has transformed the manufacture of functionally graded materials (FGMs), such as Selective Laser Melting (SLM) and Fused Filament Fabrication (FFF). The beneficial process parameters optimization is important to enhance mechanical and thermal effectiveness. SLM enables minimization of defects like porosity, cracks, through the control of laser power, scan rate and spacing between hatch by managing thermal gradients. Simulations allow forecasting and readjusting the interaction between lasers and powder and integrating models with observations provides high structural integrity when making the sample.

In the case of FFF, such factors as extrusion temperature, layer height, and print speed influence surface finish and dimension accuracy. These variables are categorized using tools like cause and effect diagrams so as to optimize in a simplified manner. Multi-material additive manufacturing will introduce a degree of versatility, where it is possible to combine various materials in a single print and have greater control over mechanical characteristics, as well as allow a functional gradient that can be designed. The localized properties are adjusted with using hybrid structures with reinforcements or fillers, without compromising the overall quality.

Although this has been led, the costs of production are prohibitive making the large-scale use of functional graded additive manufacturing less adopted than the traditional methods. Cost-benefit analysis and optimization of the processes is imperative in order to make justified investments in competitive markets.

More efficient methods are in the form of data-driven methods in particular machine learning which examines previous constructions to determine the best parameters within a short period. Machine learning can also forecast the impacts of composition variation on

performance accelerating the development phases.

The feed-back of the results of experiment to the design design leads to the continuous improvement of quality and decreases the time-to-market. The developments contribute to the uses of FGM in other areas such as aerospace and biomedical engineering, [1], [4], [8] and [13].

## **4. Emerging Engineering Applications of FGMs and FGSs**

### **4.1. Aerospace Industry Innovations using FGMs**

The aerospace industry has significantly contributed to the advancement of the deployment and establishment of the functionally graded materials (FGMs). Progressive adaptation of composition and microstructure provides tailored mechanical and thermal properties essential in aerospace components that are exposed to unfriendly environments such as high temperatures and stress levels that vary.

The depositing of these materials can be tightly controlled and the additive manufacturing techniques so far used, in particular laser metal deposition (LMD), can achieve so. As an illustration, turbine blades that include incorporation of cooling channels by FGMs increases the heat handling and retain its strength. The introduction of gradients in composition in designing of the composition to enhance mechanical performance under load (2.1) is important in designing composition on cutting weight to enhance fuel efficiency without compromising durability.

The FGMs have been found to significantly improve the hardness of those parts that withstand hard environments. Gradient alloys such as titanium based ones rely on a hardened surface and a tough core to enhance wear resistance and minimize thermal stress failures. This customization of gradients opens the design space to more design options than the conventional materials can, and makes more complicated designs possible.

FGMs are also used to conserve weight as engineers are able to save materials by allocating each part only the matching functions. This reduction of weight is also getting more significant as aircraft manufacturers aim to both produce smaller and more efficient aircraft and comply with the strict regulations concerning their emissions and fuel consumption.

Nonetheless, the issues still exist regarding the transfer of FGM technology in the daily aerospace production. Section 5.1 notes that the high price and inability to implement new methods of production slow down the rest of the acceptance. One of the most important solutions to addressing these problems is to keep on researching how to optimize the processes. Such methods as machine learning process the previous data about production to predict the most preferable conditions of the production which enhances the outcomes.

Other than metals, FGMs to aerospace parts that are made of ceramics also receive attention. They have an excellent thermal stability and wear resistance that best fits to hot areas of engines such as the combustion chambers and turbine engines where heat management is the only difference.

The aerospace will also benefit as the use of FGMs with smart technologies will help to monitor and make corrective actions in real-time during flights. These promising developments of infusing components with adaptive capabilities are explored by section 6.2.

With the constant advances in the field of material science as outlined in sub. 6.1, functional graded materials will continue to transform aerospace engineering by increasing its performance and reducing its weight, or by assisting in the development of more sustainable airplane designs, [1], [5] and [15], see figure 4.

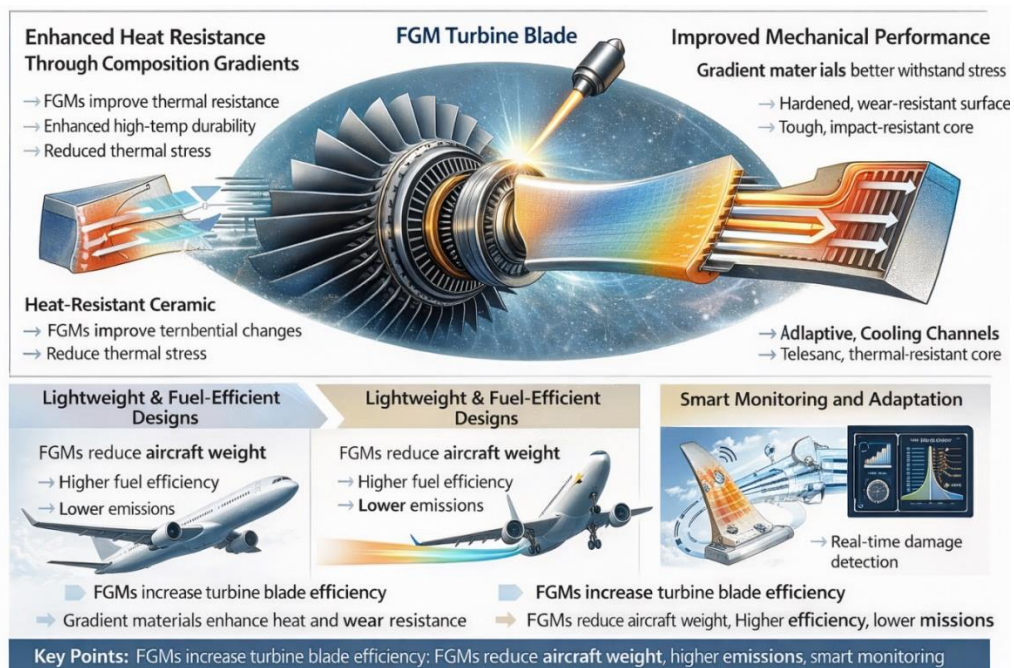


Figure 4. Aerospace Industry Innovations Using FGMs.

#### 4.2. Biomedical Applications in Tissue Engineering and Implants

The latest applications of functionally graded materials (FGMs) to biomedical applications

are in tissue engineering and orthopedic implants. Gradually changing mechanical and biological properties, FGMs formulate implants that are more like bone mechanics, integrate,

and minimize stress shielding. Natural load transfer will be promoted by this gradient design, enhancing the stability of implants.

In tissue engineering FGMs can be used to make scaffold compositions that can imitate natural tissue complexity. Microstructural aspects like the size of grains and the distribution of phases have a strong influence on performance, as these facilitate cell development and the process of tissue regeneration.

The development of additive manufacturing (AM) and selective laser melting (SLM) focuses on the improvement of FGM applications through the choice of scaffold shape on both micro and nano scales. This allows implants to be designed to suit particular anatomies, which improves the results of surgery.

The literature indicates that functional graded porosity enhances bonding of the bone since stress shielding is minimized. Porous forms make the loads evenly distributed, and they enhance bone remodeling around the implants. Indicatively, the acetabular cups which are designed to replace hips have variable porosity hence can adjust to areas of loads compared to homogeneous designs.

Hybrid lattice structures that use supraliminal materials are reported to have higher strength implants that possess properties never before seen such as auxetic behavior which is laterally expanding under tension. These properties assimilate shock in medical apparatus.

The given innovations define the fact that FGMs and AM can enhance the mechanics of implants and overcome biological issues, such as biocompatibility. Continued efforts are being in stream to perfect fabrication in order to be scale and stress free.

The development of these technologies will be augmented in future studies and prosecuted research into new composite materials is achieved to address the complex needs of biomedical usage, [16].

### 4.3. Energy Sector Developments with Functionally Graded Materials

Functionally graded materials (FGMs) have important benefits in energy sector as they hold different traits into one body. The said customization will enable FGMs to optimize mechanical strength and adjust thermal resistance and conductivity (which is crucial with applications with extreme heat or volatile conditions).

FGMs have the advantage of renewable energy devices with controlled gradients in composition. The gradients are applied to solar panels and wind turbines to enhance features on surfaces to a greater extent to increase the power collection and lifespan of the components even when loads vary.

FBGs are used in improving thermal barriers coatings and heat exchangers in heat management. Distribution of heat within their interior gradients spreads much heat effectively, and minimized thermal stress when in operation, which helps prevent fatigue and helps to make them last longer.

Multi-material additive manufacturing (MMAM) will revolutionize production of FGM offering the use of complex shapes and control of property besides minimizing wastage of materials. The method of manufacturing also provides increased design freedom to designers and enables custom parts to be fabricated with precision to the performance needs.

In projects like Grade2XL, wire arc additive manufacturing is used with the benefit of controlling locally material properties of large costly energy structures, including wind turbine blades and offshore platforms. The approach is meant to reduce lead times to as low as 96 percent and manufacture economical and quality parts.

The FGMs used together with smart technologies also optimize the energy applications. By applying sensors within graded material, real-time performance monitoring can be applied to support predictive maintenance and minimizing downtime is possible.

The studies are still addressing technical issues that are creating barriers to the wider industrial adoption. The potential of FGMs will be increased by designing sophisticated modeling and machine learning to truly comprehend the effects of processing on the structure and properties through modeling. All in all, FGMs will create innovation and sustainability when using energy technologies through enhancing efficiency and reliability in areas of critical concern, [1], [5], [13] and [17].

## **5. Challenges in Implementation and Performance Evaluation of FGAM Technologies**

### **5.1. Technical Barriers to Adoption in Industry Settings**

There are several challenging technical hurdles that impede the implementation of functionally graded materials (FGMs) in the industrial application. The biggest problem is the fact that such materials are difficult to produce, in particular, those produced with the help of additive manufacturing (AM). Despite the possibility of complex shapes and application of custom material properties, AM may also introduce variation in structural strength due to defects such as porosity and thermal residual stresses. These weaknesses can hinder the FGM efficacy and reliability in the field, which necessitates stern examination and quality control measures that have not been standardized by the industries.

The lack of knowledge of the effect of processing parameters on material structure and ultimate properties is another hitch. The various AM processes, including powder bed fusion and directed energy deposition, present their various advantages and disadvantages with regard to precision, mechanical stability and uniformity. However, the gap in the knowledge concerning the effects of tweaking of these processes on FGM behavior exists. Such uncertainty complicates the design efforts and usually results in expensive testing and error in the development.

The consideration of cost is also very problematic. Production of FGMs is often more expensive than production of standard materials due to the necessity to use specialized equipment and the time loss associated with production. These costs should be so well weighed that the companies can see the potential performance improvement, which may not be obvious at the initial or low production stages.

Another issue is presented by the unidentified standards of FGMs. In the absence of specified guidelines to this, it becomes difficult to certify these materials, particularly where the domain is regulated such as aerospace or medical equipment. The impact of lack of customized regulatory structure and tests on FGMs may cause manufacturers to be unwilling to invest in this technology.

Last but not the least resistance in the industry is something that will have its mark on the rate of adoption of FGM. Current work and supply chain processes are biased towards known materials, which work well with existing systems. This inertia requires not only technological breakthroughs but also proper communication that will illustrate the long-term benefits of functionally graded materials as compared to conventional, more traditional ones, [1], [13], [16], [17] and [18].

### **5.2. Cost-Benefit Analysis for Functionally Graded Systems**

The industries that are contemplating the use of functionally graded materials (FGMs) have to balance both their prices and advantages. FGMs are customized in mechanical and thermal properties which can be used to improve performance in most applications. The benefit of these advantages however, should be offset by the cost of manufacturing them, as well as the cost of consuming them.

A substantial part of the costs is incurred in the manufacturing, and in particular, additive technologies such as Selective Laser Melting (SLM) and Fused Deposition Modeling (FDM). The designs can be complex, but specialized equipment and materials are necessary during these methods, which add to

initial investment. It is also not easy to control defects and provide uniform quality.

In addition to the initial expenses, the recurring expenses are those of raw materials, energy, and the losses due to production mistakes. Even though FGMs might be more productive, the lifecycle costs might be greater traditional materials.

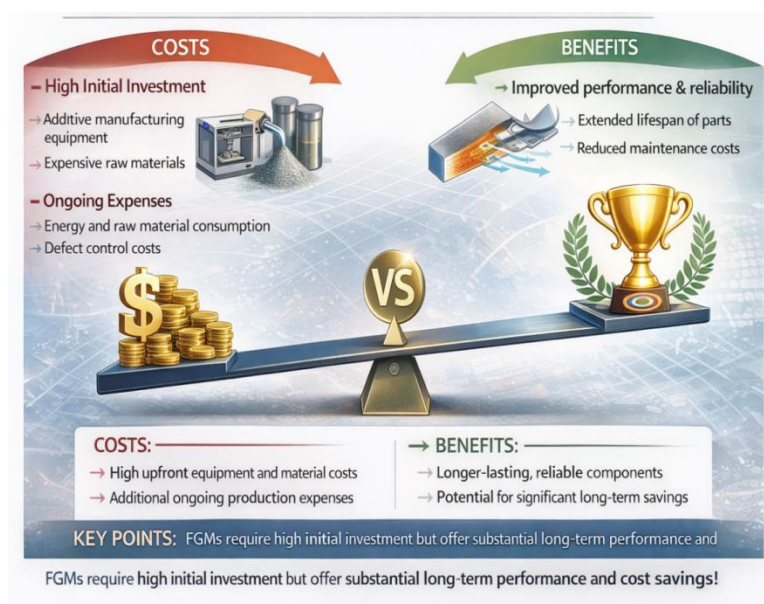
FGMs on the other hand can help cut maintenance costs and increase life of the product due to its superior life. The aerospace and healthcare industry have this level of toughness reducing down time and replacement. In this example, therefore, immediate cost should be considered and long-time savings take into account in its entirety.

Design space optimization tools (implemented through machine learning) have the potential to make designs cost-efficient and satisfy

performance objectives. These are data-driven approaches which enhance the quality and efficiency in manufacture.

The companies should also measure the demand of FGMs in the market against the traditional ones. Will the customer pay additional price on better material features? This impacts prices and positioning of products.

Lack of clear laws regarding FGMs creates confusion that can create congestions or fines. The businesses are advised to keep track of the new developments in the sphere of technologies such as smart systems to track the real-time and maintainability predictability that may even lead to the further costs reduction and the increased appeal of FGMs in the future, [1], [11] and [13], see figure 5.



**Figure 5.** Cost-Benefit Analysis for Functionally Graded Systems (FGMs).

## 6. Future Directions in Research and Development for FGMs/FGSs: Opportunities for Innovation

### 6.1. Potential Advancements in Material Science for Enhanced Properties

The recent development in the field of materials science has put the use of functional graded materials (FGMs) on the radar of engineering

innovations, which led to the development of high performing composites with highly controlled properties. Better understanding of composition change enables researchers to create gradients to increase mechanical and thermal properties tailored higher. The workforce has been in a position to create features by modifying material composition and

microstructure at small scales, which cannot be compared with the traditional uniform materials.

**Substitution** In addition to the inherent fabrication methods, such as additive manufacturing and topology optimization, advanced fabrication instruments make a significant contribution to the advancement of FGMs. The methods allow creating complex forms and customized microarchitectures, which enhance strength, firmness, and thermal resistance. Research indicates that additive processes can be combined with multi-material designs in order to enable engineers to create components that have unique, multi-functional characteristics.

Another reason that has attracted the interest of researchers to nanocomposites is its capability to reinforce FGMs with a nanoscale. The incorporation of other components like graphene or carbon nanotubes into the composite can increase tensile strength, thermal stability, and electrical conductivity by a significant margin. The breakthrough creates opportunities to be applied in aerospace, electronics, and so on.

Further, the research on negative Poisson ratio metamaterials, which are auxetic, provides an insight into the fabrication of FGMs with abnormal deformation processes. When these materials are pulled lengthwise, they swell sideways, and consequently they are also utilized in areas that require the ability to absorb energy or protect against impact.

AI and machine learning do indeed begin to leave a tangible impact by forecasting the behaviour of materials under varying circumstances. Finding the correct product, in this case, boosting the process of design and enhancing reliability by making wiser decisions of how to select the material and all the processes will be expedited by filtering large volumes of data obtained during the testing phase.

With research underway in the nano to macro scale, the future of FGMs is too bright, with all new capabilities never witnessed. Combination of innovative manufacturing processes and materials science can ensure complete new classes of materials to be used in demanding

performance correlations of diverse industries, [8], [9] and [18].

## **6.2. Integration with Smart Technology Solutions for Enhanced Functions**

The combination of functional graded material (FGMs) and smart technologies has the potential to transform most engineering disciplines. The future of fine-tuning FGMs is offered by the advances made in the field of artificial intelligence (AI) and machine learning (ML) to enable these materials to adjust their functioning in real time. This is particularly useful in such areas as aerospace, medical devices, and energy, as materials need to be responsive to changing conditions.

One of such priorities is the development of biomimetic structures with the help of AI which improves the mechanical property of FGMs. Through analysis of designs of nature, AI assists engineers to come up with graded composition that are more efficient to evenly spread stress and reduce the likelihood of failure during work. This is the result of such bio-inspired innovations that have resulted in lighter and more resistant aerospace components, which improve the fuel economy and general performance.

Combining FGMs with smart sensors goes a step further in the sense that one can have constant tracking. The sensors monitor the behaviour of materials in real time, this can be used to anticipate maintenance rather than fixing issues after they occur. The change minimizes downtimes and increases life cycles of critical parts in the industry.

In addition to the mechanical applications, FGMs are also in the ripples of smart biomedical equipment. By adding responsive elements to implants or prosthetics, these implants are able to respond to the physiological changes of the body leading to increased comfort and efficacy among the patients.

It is also this fusion that is applied to FGMs to benefit energy technologies with the help of multi-material multi-additive manufacturing (MMAM). The process creates complicated

structures capable of storing or absorbing the energy of materials to the maximum. The sustainability aspect becomes as significant as performance enhancement is provided the researchers perfect these techniques, such as recycling biodegradable materials with less difficulty.

The interaction of FGMs and intelligent systems not only simplifies the production process, but it also interacts in wider fields of industry. This combination is a promising future of producing smarter and more sustainable-engineering solutions, given that it utilizes modern design ideas and AI and other technologies, [2], [8], [13] and [18].

## 7. Conclusion: Summary of Key Insights on FGMs, FGSs, and Their Impact on Modern Engineering Practices

The use of functionally graded material structures (FGMs) and structures (FGSs) can be regarded as one of the significant developments of materials science. They enable engineers to come up with specific requirements on the design of components with specific characteristics. Compositional changes with gradual change enhance mechanical and thermal behavior, overcoming such difficulties as stress concentration, mismatch of thermal expansion in aerospace, biomedical, and energy applications.

In the last three decades, FGMs have been developed out of theoretical concepts into the practical solutions owing to the growth of manufacturing technologies such as additive manufacturing. This development allows tuning of various functions at the same time, improving the structural functioning and the methods of sustainable production. The main concept of the FGMs is that there is a control of material properties by a graded composition in a microscopic scale to enhance strength -weight ratio and heat resistance.

The possibilities are further encouraged by the functional graded additive manufacturing (FGAM) that can be used to create complex shapes that cannot be made using traditional techniques. Such methods as Fused Deposition

Modeling (FDM) are used to add various materials precisely and form parts with the specific mechanical characteristics. This maximizes the production process, minimizes flaws and maximizes efficiency.

The applications are diverse in nature of FGMs. In the aerospace industry they produce lightweight but tough components, which survive under extreme circumstances. In health care FGMs based on personalized implants prove to be easier to integrate with the tissue and reduce stress shielding which results in improved patient outcome.

Although these are the advantages, there are still problems. The complicated costs of production and materials reduce universal adoption. The expenses need to be carefully cost-benefit analysed and the costs and the benefits weighed against those in the long faces.

In the future, it is possible to employ smart technologies such as machine learning that can be integrated into the design to help speed up the process and enhance performance control. FGMs and FGSs will change the engineering field by offering tailor-made solutions and improving sustainability by developing new material and products.

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