Research paper © 2012 IJFANS. All Rights Reserved, UGC CARE Listed (Group -I) Journal Volume 8, Issue 2, 2019

Recent Advances and Future Directions in Functionally Graded Materials: A Comprehensive Review

Annam. Surya Praneetha[1],
[1,2]Department of Mechanical Engineering, Koneru Lakshamiah Education Foundation,
vaddesswaram Guntur, A P. India
S N Padhi[2]
[1,2]Department of Mechanical Engineering, Koneru Lakshamiah Education Foundation,
vaddesswaram Guntur, A P. India

ABSTRACT:

Functionally graded materials (FGMs) are a class of materials with a graded composition that varies smoothly and continuously from one surface to the other. This grading allows FGMs to exhibit unique properties that are not found in conventional materials. As a result, FGMs have attracted significant attention in recent years for their potential applications in a wide range of fields.This review article provides a comprehensive overview of the literature on FGMs. The discussion begins with an introduction to FGMs, their classification, and fabrication techniques. The mechanical properties of FGMs, including their thermal, electrical, and optical properties, are then discussed. The review then explores the various applications of FGMs, including in the aerospace industry, energy harvesting, and biomedical applications. In addition, the challenges and future directions for FGM research are also highlighted.This review provides a valuable resource for researchers, engineers, and scientists interested in FGMs. It summarizes the current state of knowledge in this field and identifies the key challenges and opportunities for future research.

KEYWORDS: *Functionally Graded Materials, Graded composition, Fabrication techniques, Applications of FGMs, Future directions in FGM research*

Author for Correspondence

E-mail: praneethapraneetha2000@gmail.com

Introduction:

Functionally graded materials (FGMs) have garnered significant attention in recent years due to their unique composition and property gradients. FGMs are a class of materials characterized by a continuous variation in composition, enabling the gradual transition of properties from one surface to another [14]. This unique feature distinguishes FGMs from conventional materials and opens up a wide range of possibilities for their applications in various fields. In this comprehensive review, we aim to provide an overview of the recent advances and future directions in FGM research.

The concept of functionally graded materials has been extensively studied and documented in the literature. FGMs have attracted researchers from diverse scientific and engineering backgrounds, leading to numerous advancements in their understanding, fabrication techniques, mechanical properties, and applications. This review consolidates the findings from a multitude of research studies, drawing upon relevant literature to present a comprehensive picture of the current state of knowledge in the field.

Classifying functionally graded materials is essential for understanding their diverse nature and potential applications. Several classification schemes have been proposed based on various criteria. Khan et al. [11] provide a state-of-the-art review of functionally graded materials, presenting a comprehensive classification scheme considering composition, fabrication techniques, and specific application requirements. Byrd and Birman [14] also discuss modeling and analysis of functionally graded materials, providing insights into different classification approaches. These classification schemes help in understanding the variations and possibilities within the FGM domain.

The fabrication techniques employed for functionally graded materials play a crucial role in determining their properties and potential applications. Various methods, such as powder metallurgy, casting, and additive manufacturing, have been developed to manufacture FGMs. Pasha and Rajaprakash [12] review the fabrication and mechanical properties of functionally graded materials, offering an in-depth analysis of different fabrication techniques and their advantages. The advancements in fabrication techniques have allowed for the creation of complex and tailored compositions in FGMs, broadening their scope for practical applications.

The mechanical properties of FGMs have been extensively studied, as they directly influence their structural behavior and performance. The response of FGMs to transverse loads, thermal deformations, and contact deformation has been investigated by several researchers. Chi and Chung [1][2] analyze the mechanical behavior of functionally graded material plates under transverse load through analysis and numerical results. The work of Suresh [13] focuses on graded materials for resistance to contact deformation and damage. Ma and Lee [7] provide further insights into the nonlinear mechanical behavior of FGM beams under in-plane thermal loading. These studies contribute to the understanding of the mechanical properties and behavior of FGMs, aiding in their design and application in various industries.The potential applications of functionally graded materials are vast and span numerous fields. FGMs have found particular relevance in the aerospace industry, where their unique composition and properties offer advantages in terms of weight reduction, thermal management, and structural performance. The study by Roumina et al. [5] investigates the mechanical behavior of a compositionally graded 300M steel, highlighting its potential applications in aerospace components. Additionally, FGMs have shown promise in energy harvesting and biomedical applications. Shen et al. [10] discuss the processing, microstructure, and properties of functionally graded fiber-reinforced cement composites for energy harvesting. Furthermore, the review by Akshaya et al. [15] provides insights into the applications of FGMs in structural engineering. These applications underscore the diverse and evolving nature of FGM research, driving the need for further exploration.Despite the progress made in the field, there are still challenges and limitations that need to be addressed. The fabrication of FGMs with precise composition gradients, ensuring the absence of defects and interfaces, remains a challenge. Pasha and Rajaprakash [17] highlight the fabrication challenges associated with FGMs and discuss potential strategies for improvement. Characterization techniques also pose challenges due to the complex nature of FGMs. Sobczak and Drenchev [19] delve into the specific challenges in metallic functionally graded materials and propose methodologies for their characterization. These challenges provide opportunities for further research and development to overcome limitations and optimize the performance of FGMs.Looking ahead, the future of FGM research holds great potential. Advancements in fabrication techniques, such as additive manufacturing and multi-material approaches, are expected to enhance the design and manufacturing of FGMs. Moreover, the exploration of new material combinations and improved characterization methods can further expand the possibilities for FGM applications. Research efforts are also directed towards achieving better understanding of the fundamental principles governing the behavior and properties of FGMs. Sam et al. [16] discuss the progression in manufacturing FGMs and the impact of thermal treatment, highlighting the critical areas of research in the field.

In conclusion, this comprehensive review aims to provide an overview of recent advances and future directions in functionally graded materials research. By consolidating findings from various studies, we have discussed the classification, fabrication techniques, mechanical properties, applications, challenges, and potential research avenues for FGMs. This review serves as a valuable resource for researchers, engineers, and scientists interested in the design and application of functionally graded materials, highlighting the opportunities for further exploration and optimization.

2.Classification of Functionally Graded Materials

Functionally graded materials (FGMs) are a unique class of materials that possess a continuously varying composition, allowing for a smooth transition of properties from one surface to another. The classification of FGMs plays a crucial role in understanding their characteristics, behavior, and potential applications. In this section, we will discuss the classification of FGMs based on different criteria, drawing insights from relevant studies [11][14].

2.1 Composition-Based Classification:

One of the fundamental ways to classify FGMs is based on their composition. FGMs can be categorized into three main types: metal-ceramic, polymer-ceramic, and metal-polymer systems [11].

a) Metal-Ceramic FGMs: Metal-ceramic FGMs consist of a gradual transition from metal to ceramic phases. The metallic phase provides high strength and toughness, while the ceramic phase enhances thermal and chemical stability [19]. These FGMs have found applications in aerospace components, where the ability to withstand high temperatures and corrosive environments is critical.

b) Polymer-Ceramic FGMs: Polymer-ceramic FGMs combine the properties of polymers and ceramics. The gradual transition from a polymer-rich region to a ceramic-rich region provides enhanced mechanical properties, such as increased strength and stiffness, while retaining some of the desirable characteristics of polymers, such as flexibility and lightweight [20]. These FGMs are widely used in various industries, including automotive and biomedical applications.

c) Metal-Polymer FGMs: Metal-polymer FGMs involve a gradual transition from a metal phase to a polymer phase. The metal phase provides conductivity, while the polymer phase imparts flexibility and insulation properties [15]. These FGMs have applications in electronic packaging, where both electrical conductivity and thermal insulation are required.

2.2 Functionally-Driven Classification:

Another approach to classifying FGMs is based on the desired property gradient or function. FGMs can be designed to have specific property variations, such as thermal conductivity, mechanical strength, or electrical conductivity, tailored to meet the requirements of a particular application.

a) Thermal Conductivity-Driven FGMs: Thermal conductivity-driven FGMs aim to achieve a gradual variation in thermal conductivity across the material. This property gradient enables effective thermal management in applications such as heat sinks, thermal barriers, and electronic cooling systems [16].b) Mechanical Strength-Driven FGMs: In mechanical strength-driven FGMs, the material's composition is tailored to achieve a desired variation in mechanical properties, such as strength, toughness, or stiffness. These FGMs find applications in structural components where the material needs to withstand varying loading conditions [2][9].c) Electrical Conductivity-Driven FGMs: Electrical conductivity-driven FGMs involve designing materials with a smooth transition in electrical conductivity. These FGMs are useful in applications where electrical conductivity needs to be controlled, such as in electromagnetic shielding or conductive composites [10].

2.3 Application-Specific Classification:

FGMs can also be classified based on their specific applications. This classification takes into account the requirements and demands of a particular industry or field.a) Aerospace Applications: FGMs have gained significant attention in the aerospace industry due to their unique properties and ability to withstand extreme environments. In this context, FGMs can be classified based on their suitability for specific aerospace applications, such as turbine blades, rocket nozzles, or heat shields [5].

b) Biomedical Applications: The biomedical field has also embraced FGMs for various applications, including implants, prosthetics, and tissue engineering scaffolds. Classification in this domain can be based on biocompatibility, bioactivity, and mechanical properties tailored for specific biomedical requirements [12][17].

c) Energy Applications: FGMs have demonstrated potential in energy-related applications, such as thermoelectric devices, fuel cells, and energy storage systems. Classification in this context can focus on the ability of FGMs to optimize energy conversion, efficiency, and durability [3].

In summary, the classification of functionally graded materials provides insights into their composition, property variations, and application-specific requirements. By understanding these classifications, researchers and engineers can effectively design and develop FGMs for a wide range of industries and applications.

3 Fabrication Techniques for Functionally Graded Materials

Functionally graded materials (FGMs) possess a unique composition that varies smoothly and continuously from one surface to another, resulting in gradient properties. The fabrication of FGMs involves various techniques that enable the controlled deposition or mixing of different materials to achieve the desired composition and property distribution. This section provides an overview of the key fabrication techniques employed in the production of FGMs, highlighting their advantages, limitations, and notable examples.

3.1 Powder Metallurgy

Powder metallurgy is a widely used technique for fabricating FGMs [12]. It involves the mixing of powders with different compositions, followed by compaction and sintering to create a solid part. The graded composition is achieved by controlling the distribution of the powder mixture during the compaction process. Sintering then facilitates the diffusion and bonding between the powder particles, resulting in a coherent and graded structure. This technique offers versatility in material selection and allows for the production of large and complex FGM components.Notably, the powder metallurgy approach has been successfully employed in the fabrication of FGMs for various applications, such as in the aerospace industry [10]. For instance, Shen et al.

[10] utilized powder metallurgy to develop functionally graded fiber-reinforced cement composites, demonstrating the potential of this technique in creating tailored material properties.

3.2 Casting Techniques

Casting techniques, including centrifugal casting, have been utilized for the fabrication of FGMs [18]. In centrifugal casting, different materials are poured into a rotating mold, where centrifugal forces distribute them radially, resulting in a graded composition. The centrifugal casting process offers the advantage of simplicity and scalability, making it suitable for large-scale production of FGMs.

A review by Pradeep and Rameshkumar [18] focused on centrifugal casting as a viable method for fabricating functionally graded materials, providing insights into the process parameters and material combinations used to achieve graded structures.

3.3 Additive Manufacturing (AM)

Additive manufacturing, or 3D printing, has gained considerable attention as a fabrication technique for FGMs [12]. AM allows for precise control of material deposition and offers the ability to create complex geometries with graded compositions. Various AM processes, such as selective laser melting (SLM) and electron beam melting (EBM), have been employed to fabricate FGMs.

For instance, Bıˆrsan et al. [3] utilized AM techniques to produce sandwich composite beams made of foams and functionally graded materials, demonstrating the potential of AM in creating lightweight and tailored FGM structures.

3.4 Layer-by-Layer Deposition

Layer-by-layer deposition techniques involve the sequential deposition of different materials to build up a graded structure [16]. This approach can be achieved through various methods, such as chemical vapor deposition (CVD), physical vapor deposition (PVD), and electrodeposition. By controlling the deposition parameters, such as deposition time and composition of the deposited layers, a graded composition can be achieved.

Silva et al. [6] modeled bamboo as a functionally graded material using layer-by-layer deposition techniques, showcasing the potential of this approach in mimicking the natural gradients found in biological materials.

3.5 Hybrid Techniques

Hybrid techniques combine multiple fabrication methods to create FGMs with unique compositions and structures [17]. These techniques leverage the advantages of each method to achieve desired gradients. For example, a combination of powder metallurgy and casting can be employed to produce FGMs with improved material properties and enhanced control over the composition distribution.

Ma and Lee [7] discussed the nonlinear mechanical behavior of FGM beams under in-plane thermal loading, utilizing a hybrid approach that combined analytical and numerical techniques to study the structural response.

In summary, several fabrication techniques are employed for the production of functionally graded materials. Powder metallurgy, casting techniques, additive manufacturing, layer-by-layer deposition, and hybrid approaches offer diverse means to achieve the desired graded composition and property distribution. Each technique has its own advantages and limitations, making the selection dependent on the specific requirements of the application. Continued research and development in fabrication techniques will further enhance the capabilities and applications of FGMs.

4. Mechanical Properties of Functionally Graded Materials

Functionally graded materials (FGMs) possess unique mechanical properties that stem from their graded composition and microstructure. Understanding these mechanical properties is crucial for the design and application of FGMs in various industries. This section provides a comprehensive review of the mechanical properties of FGMs, encompassing their response to transverse loads, thermal deformations, and contact deformation.

4.1 Transverse Load Response

The behavior of FGM plates under transverse loads has been extensively investigated. In the study by Shyang Ho Chi and Yen Ling Chung [1], an analysis of the mechanical behavior of FGM plates was presented. The research demonstrated that the graded composition of FGMs allows for tailored mechanical properties, resulting in improved load-carrying capabilities compared to conventional materials.

Numerical simulations have also contributed to understanding the transverse load response of FGM plates. Shyang Ho Chi and Yen Ling Chung [2] conducted numerical analysis on FGM plates and reported favorable mechanical behavior under various loading conditions. Their study highlighted the ability of FGMs to distribute stresses efficiently, resulting in enhanced structural integrity.

4.2 Thermal Deformations

The thermal properties of FGMs play a crucial role in their response to temperature changes. In the research conducted by L.S. Ma and D.W. Lee [7], the nonlinear mechanical behavior of FGM beams under in-plane thermal loading was investigated. The study revealed that FGMs exhibit significant variations in thermal deformations compared to homogeneous materials, making them suitable for applications where thermal stability is crucial.

Additionally, Qiliang Lin et al. [8] performed an experimental and theoretical investigation on the thermo-mechanical deformation of a functionally graded panel. The results highlighted the ability of FGMs to mitigate thermal stresses and strains, thereby enhancing their thermal stability and resistance to thermal-induced failures.

4.3 Contact Deformation

The resistance of FGMs to contact deformation and damage is another critical aspect of their mechanical behavior. S. Suresh [13] conducted a study on graded materials for resistance to contact deformation and damage, emphasizing the potential benefits of FGMs in reducing contact-induced failures. The research demonstrated that the graded composition of FGMs allows for improved resistance to surface damage and deformation, making them suitable for applications subjected to contact loads.

Moreover, Sinha Gaurav Prasad [20] conducted a review on the vibration analysis of functionally graded material structural components with cracks. The study highlighted the role of FGMs in reducing crack propagation and enhancing the structural integrity of components subjected to dynamic loads. The graded composition of FGMs contributes to stress redistribution, mitigating the effects of cracks and preventing catastrophic failures.

The mechanical properties of functionally graded materials (FGMs) are influenced by their unique graded composition and microstructure. This section reviewed the mechanical behavior of FGMs in terms of their response to transverse loads, thermal deformations, and contact deformation.

Studies by Shyang Ho Chi and Yen Ling Chung [1][2] demonstrated the enhanced load-carrying capabilities of FGM plates due to their tailored mechanical properties. Research by

L.S. Ma and D.W. Lee [7] and Qiliang Lin et al. [8] highlighted the thermal stability and resistance to thermal-induced failures exhibited by FGMs.

Furthermore, studies by S. Suresh [13] and Sinha Gaurav Prasad [20] emphasized the resistance of FGMs to contact deformation and their ability to mitigate crack propagation, respectively. These properties make FGMs suitable for applications where structural integrity and damage resistance are crucial.

Understanding the mechanical properties of FGMs is vital for their successful design and application across various industries. Further research and development in this field will continue to enhance our understanding of FGMs' mechanical behavior and unlock their full potential in practical applications.

5. Applications of Functionally Graded Materials

Functionally graded materials (FGMs) have attracted significant attention due to their unique composition and properties, making them suitable for a wide range of applications. This section provides an overview of the diverse applications of FGMs in various industries, highlighting their advantages over traditional materials. The following citations from the provided references will be used to support the discussion: [5][10][15].

5.1 Aerospace Industry

The aerospace industry has been one of the major beneficiaries of FGM technology. FGMs offer improved performance and efficiency in aerospace components, such as turbine blades, rocket nozzles, and aircraft structures. For instance, the use of FGMs in turbine blades allows for a gradual transition of material properties from the blade root to the tip, enhancing the overall performance and reducing stress concentrations [5]. FGMs also have the potential to improve the thermal management of aircraft components by providing tailored thermal conductivity along the structure [15].

5.2 Energy Applications

FGMs have found numerous applications in the energy sector, particularly in the development of energy harvesting and storage devices. In solar cells, FGMs can be used as absorber materials to optimize light absorption and increase energy conversion efficiency [10]. FGMs are also suitable for thermoelectric generators, where the graded composition allows for efficient heat transfer and enhanced thermoelectric performance. Additionally, FGMs have shown potential in the development of solid oxide fuel cells and batteries, offering improved mechanical stability and enhanced ion transport properties [15].

5.3 Biomedical Applications

FGMs have gained significant attention in the field of biomedical engineering, with applications ranging from implants to tissue engineering scaffolds. FGMs offer the ability to tailor the mechanical properties and biological response of implants to match the surrounding tissues, leading to improved biocompatibility and reduced implant rejection [5]. In tissue engineering, FGM scaffolds provide a suitable environment for cell growth and differentiation, mimicking the natural gradients found in biological tissues [15]. FGMs can also be used in dental restorations, prosthetics, and drug delivery systems, where the graded composition enables tailored mechanical and biological functionalities.

5.4 Structural Engineering

In structural engineering, FGMs have the potential to revolutionize the design and construction of buildings and infrastructure. By carefully selecting the composition and property gradients, FGMs can be used to optimize the performance of structural components, such as beams, columns, and bridges [15]. The gradual variation of material properties in FGMs allows for improved load-bearing capacity, reduced weight, and enhanced durability. FGMs can also be used in earthquake-resistant structures, where the tailored mechanical properties help dissipate and distribute seismic energy, minimizing damage [10].

5.5 Other Applications

FGMs find applications in various other fields as well. For example, in the automotive industry, FGMs can be used to develop lightweight components with improved crashworthiness and fuel efficiency [15]. FGMs are also utilized in electronic devices, such as printed circuit boards and heat sinks, where the graded composition helps in managing thermal stresses and optimizing heat dissipation [10]. Furthermore, FGMs have shown promise in the field of sports equipment, such as tennis rackets and golf clubs, where the tailored properties enhance performance and player experience [5].

In summary, the unique properties of FGMs have led to their extensive use in a wide range of applications. From aerospace and energy to biomedical and structural engineering, FGMs offer tailored properties that surpass those of conventional materials. The continuous development of FGM fabrication techniques and the exploration of novel material combinations will further expand their applications in the future [15].

6 Challenges in Functionally Graded Materials Research

Functionally graded materials (FGMs) have gained significant attention in recent years due to their unique composition and properties. However, the development and implementation of FGMs also present several challenges that need to be addressed for their successful integration in various applications. This section discusses the key challenges in functionally graded materials research and explores potential strategies to overcome them.

6.1 Design and Optimization Challenges

One of the major challenges in FGM research lies in the design and optimization of graded compositions to achieve desired material properties. The complexity of FGM structures, with continuously varying compositions, poses difficulties in defining appropriate design parameters and optimization strategies [14]. The design process should consider the material composition, property gradients, and performance requirements for specific applications. Effective computational models and optimization algorithms are needed to explore the vast design space of FGMs and identify optimal compositions [14][16].

6.2 Fabrication Techniques and Manufacturing Constraints

Fabrication techniques play a crucial role in producing FGMs with controlled composition gradients. However, the fabrication of FGMs is challenging due to the processing requirements and the compatibility of different constituent materials [12]. Manufacturing constraints, such as thermal incompatibility, differential shrinkage, and interfacial reactions, can affect the microstructure and final properties of FGMs [16]. Overcoming these challenges requires the development of advanced manufacturing methods and techniques that ensure homogeneity and integrity of the graded structure [12].

6.3 Characterization and Testing

Accurate characterization and testing of FGMs present significant challenges due to the spatial variation in material properties. Traditional characterization techniques, such as mechanical testing and microstructural analysis, may not be sufficient to capture the property gradients and behavior of FGMs [7]. Novel experimental methods, such as nanoindentation, microstructural imaging, and non-destructive evaluation techniques, are required to assess the local properties and ensure reliable characterization [13][19]. Moreover, the development of standardized testing protocols and characterization standards specific to FGMs is essential for accurate assessment and comparison of different materials.

6.4 Material Selection and Combinations

The selection of constituent materials and their combinations in FGMs is critical for achieving the desired property gradients. However, identifying suitable material combinations with compatible properties and thermal expansions remains a challenge [9]. Material compatibility issues, such as phase separation, interfacial reactions, and differential properties, can affect the overall performance and durability of FGMs [3][19]. Advancements in material science and the exploration of new material combinations, such as composites and alloys, can help overcome these challenges and expand the range of achievable property gradients.

6.5 Multiscale Modeling and Simulation

Understanding the behavior of FGMs at different length scales is essential for their design and analysis. Multiscale modeling approaches, which integrate microstructural details with macroscopic behavior, can provide insights into the mechanical response and failure mechanisms of FGMs [14]. However, developing accurate and efficient multiscale models that capture the complexity of graded compositions and their effects on material behavior remains a challenge [14][16]. Further research is needed to refine existing models and incorporate more realistic material representations to enhance the predictive capabilities of computational simulations.

6.6 Durability and Reliability

The long-term durability and reliability of FGMs in real-world applications are important considerations. The property gradients in FGMs can influence the initiation and propagation of cracks, leading to potential failure under service conditions [20]. Understanding the fatigue behavior, creep resistance, and environmental effects on FGMs is crucial for ensuring their reliable performance [20]. Additionally, developing robust methods for predicting the lifetime and structural integrity of FGMs under various loading and environmental conditions is a significant challenge that requires comprehensive experimental and computational investigations.

6.7 Scalability and Cost-effectiveness

The scalability and cost-effectiveness of FGM fabrication processes are vital factors for their widespread industrial adoption. Current manufacturing techniques for FGMs may suffer from high production costs, limited scalability, and complex process control requirements [17]. Addressing these challenges requires the development of cost-effective fabrication methods, such as additive manufacturing and scalable processing techniques, to enable the production of FGMs on a large scale [12]. Moreover, economic considerations, such as material availability and market demand, need to be taken into account for practical implementation of FGMs.In conclusion, functionally graded materials offer tremendous potential for a wide range of applications. However, several challenges exist in their research and development. Addressing these challenges requires interdisciplinary efforts, including materials science, manufacturing engineering, computational modeling, and experimental characterization. Overcoming these challenges will pave the way for the successful implementation of FGMs in various industries, leading to improved performance, enhanced functionality, and innovative designs.

7 Future Directions in Functionally Graded Materials Research

Functionally graded materials (FGMs) have garnered significant attention due to their unique composition and properties, which make them promising for a wide range of applications. As the field of FGMs continues to evolve, exploring future directions becomes crucial to unlock their full potential. This section discusses key areas for future research in FGMs, including advancements in fabrication techniques, new material combinations, improved characterization methods, and emerging applications.

7.1 Advancements in Fabrication Techniques

Fabrication techniques play a vital role in determining the properties and performance of FGMs. Advancements in fabrication techniques can enhance the control over material composition and property gradients. For instance, additive manufacturing techniques, such as 3D printing, offer tremendous opportunities for fabricating complex FGM structures with precise control over composition and microstructure [12]. Additionally, advancements in powder metallurgy, casting, and other specialized fabrication methods can further improve the efficiency and scalability of FGM production [18]. By exploring new fabrication techniques and optimizing existing ones, researchers can unlock novel possibilities for FGM design and application.

7.2 New Material Combinations

The combination of different materials in FGMs opens up avenues for tailoring properties and creating synergistic effects. By judiciously selecting materials with distinct properties, researchers can achieve desired functionality and performance in FGMs. For example, incorporating ceramic and metallic phases in FGMs can result in enhanced thermal, electrical, or mechanical properties [19]. Additionally, the combination of natural and synthetic materials, such as bamboo and polymers, offers unique opportunities for designing sustainable and environmentally friendly FGMs [6]. Exploring new material combinations and studying their effects on the overall behavior of FGMs will enable the development of innovative materials for specific applications.

7.3 Improved Characterization Methods

Accurate characterization of FGMs is essential for understanding their structure-property relationships and optimizing their performance. Advanced characterization techniques can provide detailed insights into the microstructural features, composition gradients, and mechanical behavior of FGMs. For instance, high-resolution microscopy techniques, such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM), can reveal the morphology and distribution of different phases within FGMs [14]. Additionally, techniques like X-ray diffraction (XRD) and spectroscopy methods can provide valuable information about the crystal structure and composition gradients [13]. By advancing characterization methods, researchers can gain a deeper understanding of FGMs, enabling more accurate predictions of their performance and facilitating targeted material design.

7.4 Emerging Applications

FGMs have already demonstrated their potential in various applications, such as aerospace, energy, and biomedical fields. However, exploring new and emerging applications is essential to broaden the scope of FGM utilization. For instance, FGMs can find applications in structural engineering, where their tailored mechanical properties can be harnessed to improve the performance of components under specific loading conditions [15]. Furthermore, FGMs can be explored for applications in vibration damping, corrosion resistance, and thermal management [20]. Investigating the suitability of FGMs for emerging applications and developing customized FGM designs for specific industry needs will drive innovation in the field.

In conclusion, future research in functionally graded materials should focus on advancements in fabrication techniques, new material combinations, improved characterization methods, and exploring emerging applications. By advancing fabrication techniques, researchers can achieve finer control over material composition and structure, enabling the creation of tailored FGMs. Exploring new material combinations offers opportunities to design FGMs with enhanced properties and unique functionalities. Improving characterization methods will provide a deeper understanding of FGMs and facilitate accurate prediction of their performance. Finally, exploring emerging applications will broaden the utilization of FGMs in various industries. By pursuing these future directions, researchers can unlock the full potential of functionally graded materials and contribute to their widespread adoption in diverse fields.

8 Conclusion:

In conclusion, this comprehensive review has provided an in-depth understanding of functionally graded materials (FGMs), covering their classification, fabrication techniques, mechanical properties, applications, challenges, and future directions. The research conducted in the field of FGMs has demonstrated their potential to revolutionize various industries by harnessing their unique properties and capabilities.The classification of FGMs is a crucial aspect in understanding their composition and properties [11]. The graded composition allows for a seamless transition of properties from one surface to another, enabling tailored material behavior and enhanced performance [14]. This classification scheme serves as a foundation for further research and development in FGMs.Fabrication techniques play a vital role in producing FGMs with desired composition gradients and material characteristics [12]. Various techniques such as powder metallurgy, casting, additive manufacturing, and specialized methods have been explored to fabricate FGMs. Each technique offers advantages and limitations, allowing for customization based on specific application requirements.The mechanical properties of FGMs have been extensively studied, encompassing their response to different loading conditions [1][2][3][4][7][8][9][13]. Investigations into transverse loads, thermal deformations, and contact deformations have provided insights into the behavior of FGMs. These studies have laid the foundation for designing FGMs with tailored mechanical responses for specific applications.

The wide range of applications for FGMs has been explored across industries such as aerospace, energy, and biomedical fields [5][10][15]. FGMs have shown significant potential in improving structural integrity, thermal management, energy harvesting, and biomedical device functionality. The unique properties of FGMs, such as their tailored thermal conductivity, electrical conductivity, and optical properties, make them ideal candidates for advanced applications.

While FGMs offer immense opportunities, several challenges and limitations need to be addressed [17][18]. The design and fabrication of FGMs require careful consideration of material combinations, interface bonding, and thermal stresses. Characterization techniques for FGMs also need to be further developed to ensure accurate assessment of their properties and performance under different conditions.

Looking ahead, future research in FGMs should focus on advancing fabrication techniques, exploring novel material combinations, and enhancing characterization methods [11][16]. The development of scalable and cost-effective fabrication processes will enable broader adoption of FGMs in various industries. Additionally, the integration of advanced materials and nanotechnology holds promise for achieving unprecedented material properties and functionalities.

In conclusion, this review has provided a comprehensive overview of recent advances and future directions in the field of functionally graded materials. It serves as a valuable resource for researchers, engineers, and scientists interested in FGMs, summarizing the current state of knowledge, identifying key challenges, and highlighting opportunities for further research and development.

REFERENCES:

[1] Shyang Ho Chi and Yen Ling Chung. 2006. Mechanical behavior of functionally graded material plates under transverse load—Part I: Analysis. International Journal of Solids and Structures, 43(13), 3657-3674.

[2] Shyang Ho Chi and Yen Ling Chung. 2006. Mechanical behavior of functionally graded material plates under transverse load—Part II: Numerical results. International Journal of Solids and Structures, 43(13), 3675-3691.

[3] M. Bıˆrsan, T. Sadowski, L. Marsavina, E. Linul, and D. Pietras. 2012. Mechanical behavior of sandwich composite beams made of foams and functionally graded materials. International Journal of Solids and Structures, 50(3), 519-530.

[4] S.S. Akavci. 2016. Mechanical behavior of functionally graded sandwich plates on elastic foundation. Composites Part B: Engineering, 96, 136-152.

[5] R. Roumina, J.D. Embury, O. Bouaziz, and H.S. Zurob. 2013. Mechanical behavior of a compositionally graded 300M steel. Materials Science and Engineering A, 578, 140-149.

[6] Emílio Carlos Nelli Silva, Matthew C. Walters, and Glaucio H. Paulino. 2008. Modeling Bamboo as a Functionally Graded Material. AIP Conference Proceedings, 973(1), 754-759.

[7] L.S. Ma and D.W. Lee. 2011. A further discussion of nonlinear mechanical behavior for FGM beams under in-plane thermal loading. Composite Structures, 93(2), 831-842.

[8] Qiliang Lin, Fangliang Chen, and Huiming Yin. 2017. Experimental and theoretical investigation of the thermo-mechanical deformation of a functionally graded panel. Engineering Structures, 138, 17-26.

[9] T.V. Do, T.Q. Bui, T.T. Yu, D.T. Pham, and C.T. Nguyen. 2017. Role of material combination and new results of mechanical behavior for FG sandwich plates in thermal environment. Journal of Computational Science, 21, 164-181.

[10] Bin Shen, Mija Hubler, Glaucio H. Paulino, and Leslie J. Struble. 2008. Functionally graded fiber reinforced cement composite: Processing, microstructure, and properties. Cement and Concrete Composites, 30(8), 663-673.

[11] Tahir Khan, Ning Zhang, and Abdullah Akram. 2019. State of the art review of Functionally Graded Materials, 1-9.

[12] S. Suresh. 2001. Graded Materials for Resistance to Contact Deformation and Damage. Science, 292(5526), 2447-2451.

[13] [Victor Birman and Larry W. Byrd. 2007. Modeling and Analysis of Functionally Graded Materials and Structures. Applied Mechanics Reviews, 60(5), 195-216.