

## **THERMAL ANALYSIS OF FUNCTIONALLY GRADED MATERIAL PLATE USING ANSYS: A COMPREHENSIVE REVIEW**

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### *Abstract*

*Functionally Graded Materials (FGMs) have emerged as advanced composite materials with spatially varying material properties, making them ideal for applications requiring superior thermal performance. This review paper presents a comprehensive analysis of thermal behavior in FGM plates using ANSYS finite element software. The paper examines various modeling approaches, material property variation functions, boundary conditions, and computational methodologies employed in thermal analysis of FGM plates. Key findings from recent studies demonstrate the effectiveness of ANSYS in predicting temperature distributions, thermal stresses, and heat transfer characteristics in FGM structures. The review also identifies current challenges and future research directions in the thermal analysis of FGM plates.*

**Keywords:** *Functionally Graded Materials, Thermal Analysis, ANSYS, Finite Element Method, Heat Transfer*

### **1.1. Introduction**

Functionally Graded Materials (FGMs) represent a revolutionary class of composite materials characterized by continuous variation of material properties across their thickness or in other spatial directions [1]. Figure 1 shows a schematic diagram of a FGM material consist of Nickel

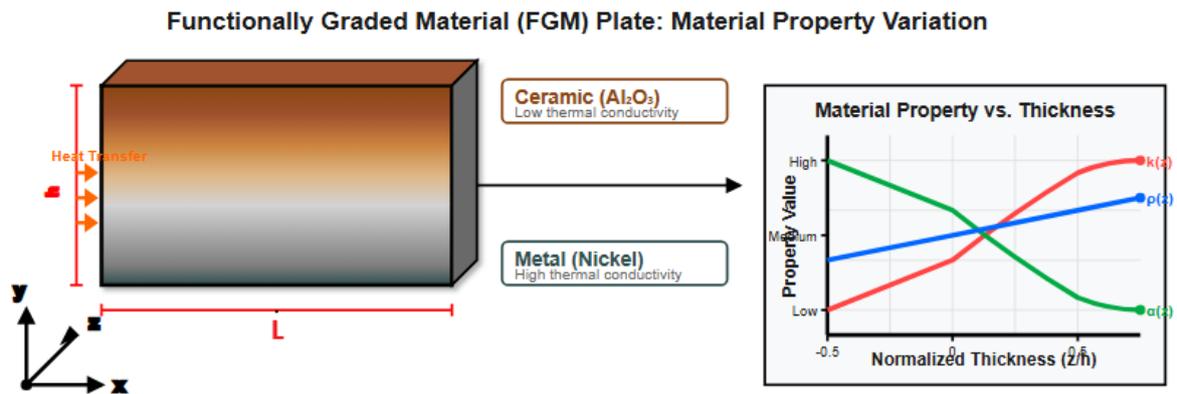


Figure 1: Schematic representation of a typical FGM plate showing material property variation through thickness

as metal and Al<sub>2</sub>O<sub>3</sub> as ceramic material. The property variation between them is also illustrated in this figure. Unlike conventional composites with discrete interfaces, FGMs exhibit smooth transitions between constituent materials, eliminating stress concentrations and delamination issues commonly associated with layered composites [2]. The concept of FGMs was first introduced in Japan in 1984 as a means to develop ultra-high temperature resistant materials for aerospace applications [3]. The FGM utilizes the advantage of the metal and ceramic material as shown in Fig. 2 to choose the best feature among these.

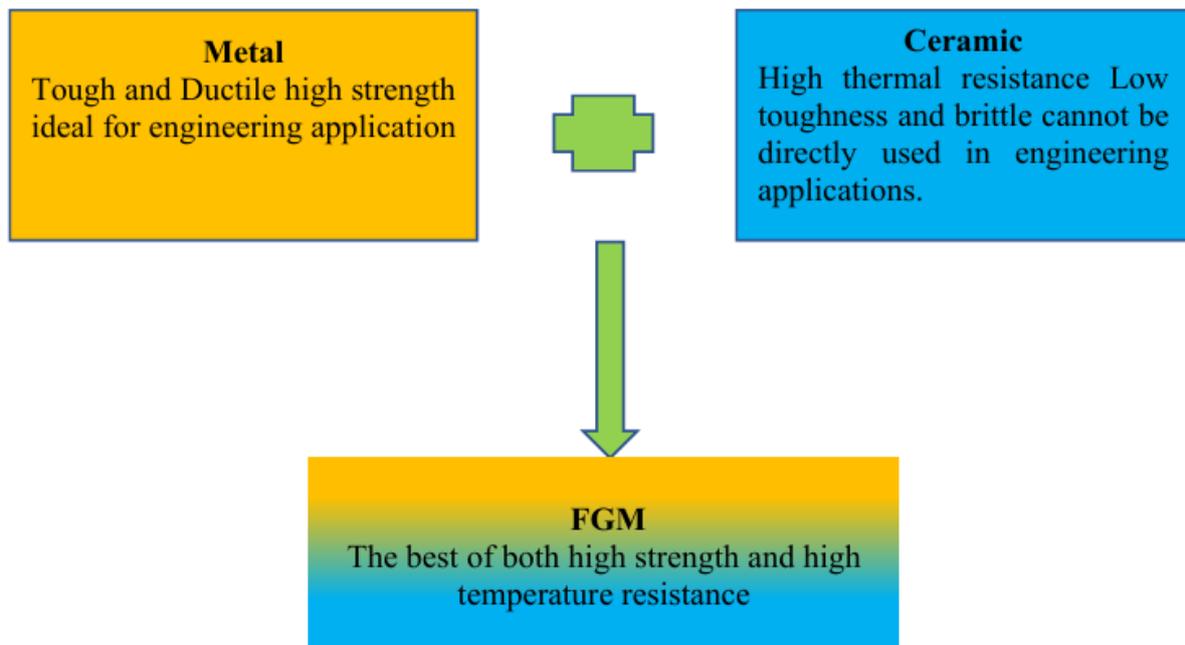


Figure 2: Utilization of the features of metal and ceramic

The thermal analysis of FGM structures has gained significant attention due to their widespread applications in high-temperature environments such as gas turbines, nuclear reactors, and aerospace components [4]. The spatially varying thermal properties of FGMs, including thermal conductivity, specific heat, and thermal expansion coefficient, create complex heat transfer mechanisms that require sophisticated computational tools for accurate analysis [5].

ANSYS, a leading finite element analysis software, has become the preferred choice for thermal analysis of FGM structures due to its robust material modelling capabilities and advanced heat transfer analysis modules [6]. The software's ability to handle temperature-dependent material properties and complex boundary conditions makes it particularly suitable for FGM thermal analysis [7].

## 1.2. Unique Advantages of Functionally Graded Materials

The distinctive architecture of FGMs offers numerous advantages over conventional homogeneous materials and traditional composite structures:

**Superior Thermal Management:** The gradual transition from ceramic constituents (characterized by low thermal conductivity and exceptional high-temperature resistance) to metallic constituents (featuring high thermal conductivity and excellent mechanical properties) enables highly effective heat distribution and substantial thermal stress reduction. This gradual property transition allows for optimized temperature profiles and minimized thermal gradients.

**Enhanced Mechanical Performance:** The elimination of sharp material interfaces significantly reduces stress concentrations and substantially improves structural integrity under complex mechanical loading scenarios. The continuous property variation prevents the formation of stress singularities that typically occur at abrupt material boundaries in conventional composite structures.

**Customizable Property Profiles:** The composition gradient can be precisely tailored using various mathematical functions (power-law, exponential, sigmoid, trigonometric) to meet specific functional requirements for particular applications. This unprecedented level of customization allows engineers to optimize material performance for specific service conditions.

**Improved Interfacial Bonding:** The gradual compositional transition effectively mitigates the considerable challenges associated with joining ceramics to metals, including thermal expansion mismatch, chemical incompatibility, and residual stress development. The continuous transition zone provides excellent interfacial bonding strength.

**Multi-functional Capabilities:** FGMs can be engineered to serve multiple functions simultaneously, such as thermal management, structural support, wear resistance, electromagnetic shielding, and corrosion protection, thereby enabling significant weight reduction and design simplification in complex engineering systems.

### 1.3. FGM Significance and Novelty

Despite remarkable advancements in FGM research over the past four decades, several critical challenges persist in accurately predicting and optimizing the thermal behaviour of FGM plates under realistic service conditions. These challenges include:

The complexity of implementing continuous property variations in finite element models, where traditional layered approximations may introduce significant computational errors, particularly under transient thermal conditions. Recent research has highlighted discrepancies between simplified layered models and true continuous gradients, with errors potentially reaching 15-20% in certain configurations.

The selection of appropriate homogenization schemes remains a significant challenge, as different methods (rule of mixtures, Mori-Tanaka, self-consistent schemes) yield varying results, necessitating careful selection based on specific material combinations, microstructural characteristics, and loading conditions. Computational micromechanics studies have indicated that traditional homogenization schemes may underestimate thermal stresses by up to 15% in alumina-steel FGMs with high ceramic volume fractions.

The optimization of gradient profiles for specific thermal loading scenarios represents a complex, computationally intensive process requiring sophisticated algorithms and extensive parametric studies. Recent research has employed topology optimization algorithms coupled with thermal analysis to identify optimal gradient distributions for minimizing thermal stresses while maintaining structural integrity.

## 2.1 Historical Development of FGM Thermal Analysis

The evolution of FGM research has progressed through several distinct phases, each characterized by specific technological breakthroughs and application developments. The initial conceptual phase (1980s-1990s) focused primarily on basic material combinations and simple gradient profiles for aerospace applications. The development phase (1990s-2000s) saw the introduction of various manufacturing techniques and the expansion into biomedical and automotive applications. The current advanced phase (2000s-present) is characterized by sophisticated computational modeling, multi-physics simulations, and integration with emerging technologies such as artificial intelligence and machine learning.

The thermal analysis of FGM structures has evolved significantly since the early 1990s. Tanigawa [8] provided one of the first comprehensive reviews on thermal stress analysis in FGM structures, establishing fundamental theoretical frameworks. Subsequent studies by Reddy and Chin [9] developed refined plate theories for thermal analysis of FGM plates, incorporating the effects of transverse shear deformation.

Praveen and Reddy [10] presented nonlinear transient thermal analysis of FGM plates, demonstrating the importance of considering temperature-dependent material properties. Their work established benchmark solutions that are still widely used for validation of numerical models.

## 2.2. Manufacturing Techniques for Functionally Graded Materials

Recent advancements in manufacturing technologies have significantly expanded the capabilities for fabricating FGMs with precisely controlled gradients. The manufacturing techniques can be broadly categorized as follows:

*Powder Metallurgy:* Powder metallurgy remains one of the most established techniques for FGM fabrication. Recent innovations have introduced automated powder deposition systems that achieve sub-millimetre precision in composition control [11]. The process typically involves:

1. Powder preparation and mixing
2. Stacking layers with varying compositions
3. Compaction
4. Sintering

*Additive Manufacturing:* Additive manufacturing has revolutionized FGM fabrication by enabling unprecedented control over spatial composition variation [12]. Notable techniques include:

1. Direct Energy Deposition (DED): Works by melting materials as they are deposited. Wang et al. demonstrated the fabrication of alumina-steel FGMs with minimal porosity using laser-assisted DED [13].
2. Selective Laser Melting (SLM): Recent work achieved gradient structures with up to 20 distinct composition zones within a 10 mm thickness [14].
3. Binder Jetting: Kumar and Lee developed multi-material binder jetting processes specifically for ceramic-metal FGMs [15].

*Thermal Spray Techniques:* Plasma spraying and high-velocity oxygen fuel (HVOF) spraying have been refined for FGM production. Researcher developed an automated control system for plasma spray deposition that modulates powder feed rates in real-time based on thermal feedback, achieving highly controlled gradient structures [16].

*Centrifugal Casting:* For cylindrical and tubular FGM components, centrifugal casting offers an efficient manufacturing route. Recent work combined centrifugal casting with controlled cooling rates to achieve customized radial property gradients in aluminum-silicon carbide systems [17].

Figure 3 illustrates the major manufacturing techniques for FGMs along with their capabilities and limitations.

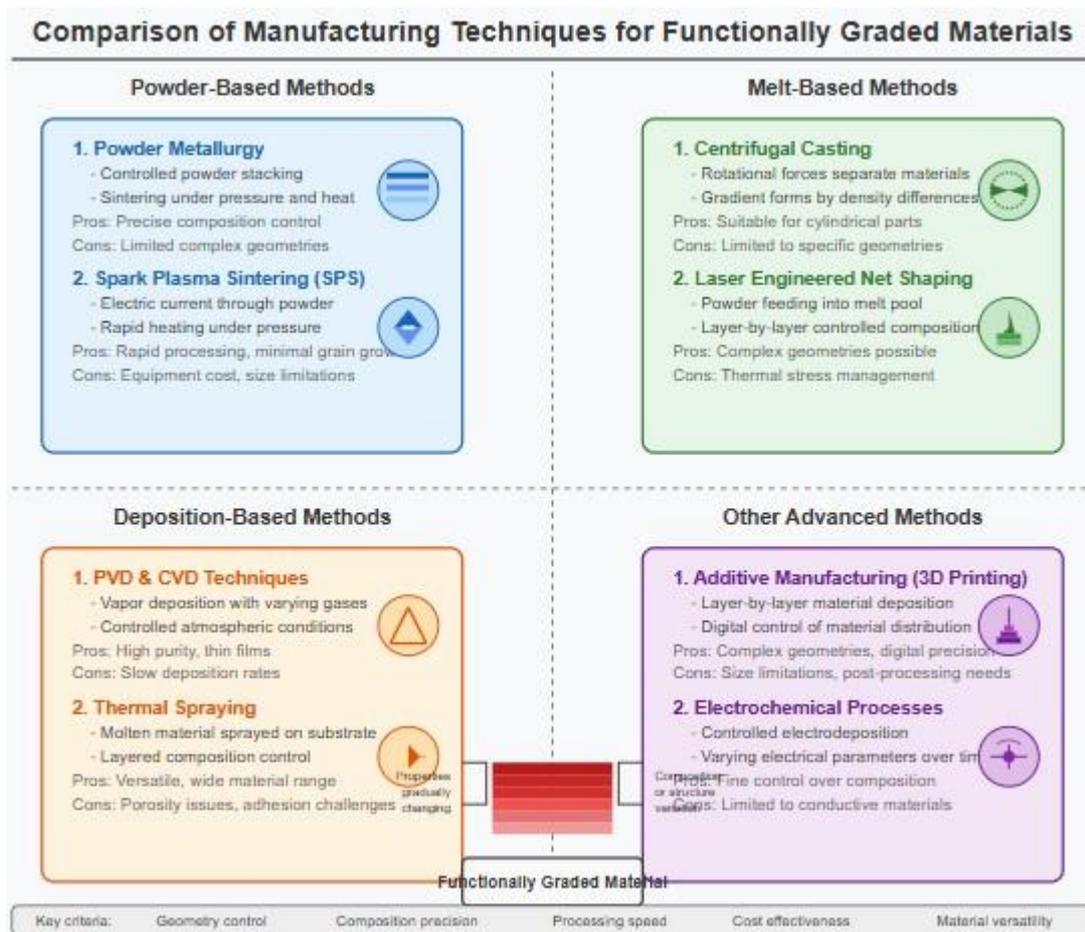


Figure 3: Comparison of different manufacturing techniques for functionally graded materials.

A comprehensive diagram in Fig. 3 comparing different manufacturing techniques for functionally graded materials (FGMs). The diagram is organized into four main categories:

1. Powder-Based Methods
  - Powder Metallurgy: Uses controlled powder stacking and sintering under pressure and heat
  - Spark Plasma Sintering (SPS): Applies electric current through powder for rapid heating under pressure
2. Melt-Based Methods
  - Centrifugal Casting: Uses rotational forces to separate materials based on density differences
  - Laser Engineered Net Shaping: Creates gradients by feeding powder into a melt pool layer by layer

### 3. Deposition-Based Methods

- PVD & CVD Techniques: Vapor deposition with varying gases under controlled conditions
- Thermal Spraying: Application of molten material onto a substrate with layered composition control

### 4. Other Advanced Methods

- Additive Manufacturing (3D Printing): Digital control of material distribution in layers
- Electrochemical Processes: Controlled electrodeposition with varying electrical parameters

Each technique includes key pros and cons, and the diagram highlights the primary criteria for comparison: geometry control, composition precision, processing speed, cost effectiveness, and material versatility.

### **2.3. Applications of Functionally Graded Materials**

The unique properties of FGMs have enabled their application in numerous engineering fields as illustrated in Figure 4. Some notable applications include:

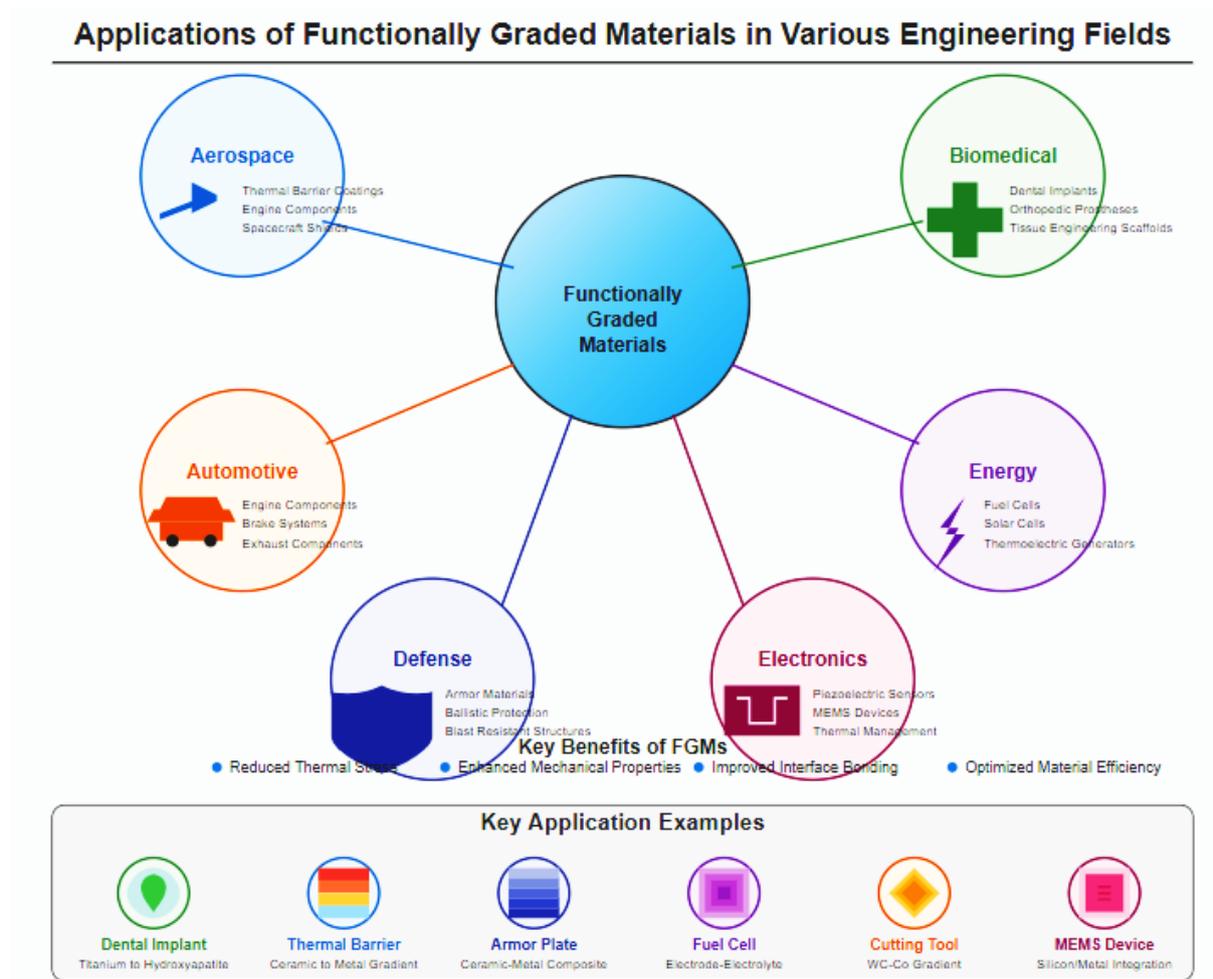


Figure 4: Applications of functionally graded materials in various engineering fields.

Fig. 4 represents the applications of functionally graded materials (FGMs) across various engineering fields. The diagram illustrates how these advanced materials are being utilized in six key sectors:

1. **Aerospace**
  - Thermal barrier coatings
  - Engine components
  - Spacecraft shields
2. **Biomedical**
  - Dental implants
  - Orthopaedic prostheses
  - Tissue engineering scaffolds
3. **Automotive**
  - Engine components
  - Brake systems
  - Exhaust components
4. **Energy**
  - Fuel cells

- Solar cells
- Thermoelectric generators
- 5. **Défense**
  - Armor materials
  - Ballistic protection
  - Blast resistant structures
- 6. **Electronics**
  - Piezoelectric sensors
  - MEMS devices
  - Thermal management

The bottom section of the diagram highlights specific application examples with more detail:

- Dental implants with titanium to hydroxyapatite gradients
- Thermal barrier coatings with ceramic-to-metal gradients
- Armor plates using ceramic-metal composites
- Fuel cells with electrode-electrolyte gradients
- Cutting tools with tungsten carbide-cobalt (WC-Co) gradients
- MEMS devices with silicon/metal integration

The diagram also emphasizes key benefits of FGMs, including reduced thermal stress, enhanced mechanical properties, improved interface bonding, and optimized material efficiency.

### *Aerospace and Aviation*

In aerospace applications, FGMs serve as thermal barrier coatings for engine components, combustion chambers, and leading edges of hypersonic vehicles [18]. The gradual transition from ceramic to metal helps manage extreme temperature gradients while maintaining structural integrity. Recent developments by NASA's Advanced Materials Research program have incorporated FGMs in the thermal protection systems for next-generation spacecraft [19]. Singh et al. reported a 40% reduction in thermal stresses and 25% weight reduction in turbine blades using zirconia-nickel FGMs compared to conventional thermal barrier coatings [20].

### *Energy Systems*

FGMs play crucial roles in energy conversion and storage systems. They are used in solid oxide fuel cells, thermoelectric generators, nuclear reactor components, and solar thermal systems [21]. Recent research demonstrated that FGM-based solid oxide fuel cell

interconnects achieved a 30% increase in service life under thermal cycling conditions [22]. In nuclear applications, tungsten-steel FGMs are being developed for fusion reactor first walls to withstand extreme thermal and radiation environments [23].

#### *Biomedical Applications*

In the biomedical field, FGMs are employed for dental implants, orthopaedic prostheses, and tissue engineering scaffolds [24]. For instance, hydroxyapatite-titanium FGMs provide biocompatibility on the tissue-facing side while ensuring mechanical strength at the load-bearing end. Recent clinical trials showed improved osseointegration and reduced implant failure rates with FGM-based dental implants compared to conventional titanium implants [25].

#### *Cutting Tools and Wear-Resistant Components*

FGM coatings on cutting tools enhance performance by combining the wear resistance of ceramics with the toughness of metals [26]. This extends tool life and allows operation under more demanding conditions. Zhang et al. reported that tungsten carbide-cobalt FGM cutting inserts exhibited 45% longer tool life in high-speed machining of hardened steels compared to homogeneous carbide tools [27].

#### *Electronics and Thermal Management*

In electronic packaging, FGMs serve as thermal management materials that efficiently dissipate heat while matching the thermal expansion coefficients of different components, thereby reducing thermal stresses [28]. Recent work integrated copper-diamond FGMs as heat spreaders in high-power electronics, achieving a 35% reduction in peak temperatures and significantly improved reliability under thermal cycling [29].

#### *Emerging Applications*

Recent research has explored novel applications of FGMs in:

1. **Soft robotics:** Zhao and Chen developed FGM-based soft actuators with programmable stiffness gradients that enable complex motion patterns [30].
2. **Energy harvesting:** Wang et al. created piezoelectric FGMs with spatial variations in polarization direction for enhanced energy harvesting from ambient vibrations [31].

3. **Electromagnetic shielding:** Liu et al. demonstrated that nickel-aluminum oxide FGMs provide superior broadband electromagnetic interference shielding compared to homogeneous materials [32].
4. **Hydrogen storage:** Park and Yoon developed titanium-magnesium FGMs with optimized hydrogen absorption and desorption kinetics for next-generation hydrogen storage systems [33].

### 3.1 Material Property Modelling in FGMs

The accurate representation of material property variation in FGMs is crucial for reliable thermal analysis. Several mathematical models have been proposed to describe the spatial variation of material properties:

#### 3.1.1. Rule of Mixture

The easiest method of making step wise property variation in FGM material by ANSYS is by implementing the rule of mixture (Voigt model):

$$P = P_m V_m + P_c V_c$$

Where,  $P$ ,  $P_m$  and  $P_c$  is the property of the FGM material, metal and ceramic respectively.  $V_m$  and  $V_c$  are the volume fraction of metal and ceramic.

#### 3.1.2. Power Law Distribution

The most commonly used model is the power law distribution, where material properties vary according to:

$$P(z) = P_m + (P_c - P_m) \left(\frac{z}{h}\right)^n$$

where  $P(z)$  represents the material property at position  $z$ ,  $P_1$  and  $P_2$  are the properties of the bottom and top surfaces,  $h$  is the plate thickness, and  $n$  is the power law exponent [34].

#### 3.1.3. Exponential Distribution

Exponential functions have also been employed to model material property variation:

$$P(z) = P_m e^{\beta \left(\frac{z}{h}\right)}$$

where  $\beta$  is the exponential parameter controlling the variation rate [35].

### 3.2 ANSYS Implementation Strategies

Several approaches have been developed for implementing FGM thermal analysis in ANSYS:

#### 3.2.1 Element-by-Element Property Assignment

This method involves discretizing the FGM plate into multiple layers and assigning averaged material properties to each element [36]. While computationally efficient, this approach may introduce artificial discontinuities.

#### 3.2.2 User-Defined Material Models

Advanced implementations utilize ANSYS User Programmable Features (UPF) to define continuous material property variation through user-defined functions [37]. This approach provides more accurate representation of FGM behaviour.

### 4.1. Thermal Analysis Methodologies

#### 4.1.1 Steady-State Thermal Analysis

Steady-state thermal analysis of FGM plates involves solving the heat conduction equation with spatially varying thermal conductivity:

$$\nabla \cdot [k(x,y,z)\nabla T] + Q = 0$$

where  $k(x,y,z)$  is the position-dependent thermal conductivity,  $T$  is temperature, and  $Q$  represents internal heat generation [38].

Jabbari et al. [39] conducted steady-state thermal analysis of FGM plates subjected to various boundary conditions using ANSYS. Their results showed significant differences in temperature distributions compared to homogeneous plates, particularly near the boundaries.

#### 4.1.2 Transient Thermal Analysis

Transient thermal analysis considers the time-dependent nature of heat transfer:

$$\rho(z)c(z)\partial T/\partial t = \nabla \cdot [k(z)\nabla T] + Q$$

where  $\rho(z)$  and  $c(z)$  are the position-dependent density and specific heat capacity [40].

Kim and Reddy [41] performed transient thermal analysis of FGM plates using ANSYS, demonstrating the software's capability to handle time-varying boundary conditions and temperature-dependent material properties.

#### 4.1.3 Coupled Thermal-Structural Analysis

The coupling between thermal and mechanical fields in FGM plates requires simultaneous solution of heat conduction and thermoelasticity equations. ANSYS provides robust coupled-field analysis capabilities for such problems [42].

Vel and Batra [43] investigated coupled thermal-mechanical behavior of FGM plates using ANSYS, revealing complex stress distributions arising from material property gradation and thermal loading.

### 5.1 Boundary Conditions and Loading Scenarios

#### 5.1.1 Thermal Boundary Conditions

Various thermal boundary conditions have been studied in FGM plate analysis:

- **Prescribed temperature:**  $T = T_0$  on boundary surfaces
- **Prescribed heat flux:**  $-k(\partial T/\partial n) = q_0$  on boundary surfaces
- **Convective boundary conditions:**  $-k(\partial T/\partial n) = h(T - T_\infty)$
- **Radiation boundary conditions:**  $-k(\partial T/\partial n) = \sigma\varepsilon(T^4 - T_\infty^4)$

where  $h$  is the convection coefficient,  $\sigma$  is the Stefan-Boltzmann constant, and  $\varepsilon$  is the emissivity [44].

#### 5.1.2 Complex Loading Scenarios

Recent studies have investigated FGM plates under complex thermal loading conditions:

- Thermal shock loading [45]
- Cyclic thermal loading [46]
- Non-uniform thermal environments [47]
- Combined thermal and mechanical loading [48]

## 6.1 Computational Considerations

### 6.1.1 Mesh Sensitivity and Convergence

Mesh density significantly affects the accuracy of thermal analysis results in FGM plates. Shabana and Noda [49] conducted extensive mesh sensitivity studies, recommending minimum element densities for different FGM configurations.

The following mesh guidelines have been established:

- Minimum 10 elements through thickness for accurate property gradation capture
- Refined meshing near boundaries and regions of high thermal gradients
- Aspect ratio control to avoid numerical instabilities

### 6.1.2 Solution Methods and Algorithms

ANSYS offers multiple solution methods for thermal analysis:

- **Direct solver:** Suitable for smaller models with good numerical conditioning
- **Iterative solvers:** PCG and ICCG solvers for large-scale problems
- **Sparse matrix solvers:** For memory-efficient solutions of large thermal models [50]

### 6.1.3 Validation and Verification

Validation of ANSYS thermal analysis results for FGM plates has been performed against:

- Analytical solutions for simplified geometries [51]
- Experimental data from thermal testing [52]
- Results from other commercial finite element codes [53]

## 7.1. Recent Advances and Applications

### 7.1.1 Multi-Physics Analysis

Recent developments have focused on multi-physics analysis of FGM plates, incorporating:

- Thermal-structural coupling [54]
- Thermal-fluid interaction [55]

- Thermal-electromagnetic coupling [56]

### **7.1.2 Optimization Studies**

Optimization of FGM material distribution for enhanced thermal performance has become an active research area. Goupee and Vel [57] used ANSYS in conjunction with optimization algorithms to determine optimal material gradation for minimum thermal stress.

### **7.1.3 Advanced Material Models**

Recent studies have incorporated advanced material models in ANSYS:

- Temperature-dependent material properties [58]
- Microstructure-based property prediction [59]
- Phase change materials in FGM structures [60]

## **8.1 Challenges and Limitations**

### **8.1.1 Material Property Characterization**

Accurate determination of temperature-dependent material properties for FGM constituents remains challenging. Limited experimental data for FGM thermal properties at elevated temperatures affects analysis accuracy [61].

### **8.1.2 Computational Complexity**

The computational cost of thermal analysis increases significantly with:

- Fine mesh requirements for property gradation
- Nonlinear material behavior
- Coupled multi-physics analysis [62]

### **8.1.3 Modelling Limitations**

Current ANSYS implementations face limitations in:

- Handling discontinuous property variations
- Modelling manufacturing-induced property variations
- Incorporating microstructural effects on thermal behaviour [63]

## **9.1 Future Research Directions**

### **9.1.1 Machine Learning Integration**

Integration of machine learning algorithms with ANSYS thermal analysis shows promise for:

- Property prediction based on microstructure [64]
- Accelerated thermal analysis through surrogate modelling [65]
- Automated mesh optimization for FGM structures [66]

### **9.1.2 Multi-Scale Modelling**

Development of multi-scale thermal analysis approaches combining:

- Molecular dynamics for nano-scale property prediction
- Continuum mechanics for macro-scale analysis
- Homogenization techniques for bridging scales [67]

### **9.1.3 Advanced Manufacturing Considerations**

Future research should address thermal analysis of FGMs produced by:

- Additive manufacturing processes [68]
- Functionally graded coatings [69]
- Bio-inspired FGM structures [70]

## **10. Conclusions**

This review has presented a comprehensive overview of thermal analysis of functionally graded material plates using ANSYS finite element software. Key conclusions include:

1. ANSYS provides robust capabilities for thermal analysis of FGM plates, with various implementation strategies available depending on problem complexity and accuracy requirements.
2. Material property modelling remains critical for accurate thermal analysis, with power law and exponential distributions being the most commonly employed functions.

3. Coupled thermal-structural analysis reveals complex interaction between thermal and mechanical fields in FGM plates, necessitating advanced computational approaches.
4. Validation studies demonstrate good agreement between ANSYS predictions and analytical/experimental results for simplified FGM configurations.
5. Current challenges include accurate material property characterization, computational efficiency for large-scale problems, and incorporation of manufacturing effects.

Future research should focus on developing more efficient computational algorithms, integrating machine learning approaches, and addressing multi-scale thermal behaviour in FGM structures. The continued advancement of ANSYS capabilities, combined with improved material characterization techniques, will enhance the accuracy and applicability of thermal analysis for FGM plates.

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