
Functionally Graded Materials: A Comprehensive Review

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Abstract

Functionally Graded Materials (FGMs) represent a paradigm shift from traditional composites by introducing continuous spatial variation in composition and microstructure. First conceptualized in Japan in 1984 for space plane thermal barriers, FGMs are engineered to withstand extreme thermal, mechanical and chemical gradients without interfacial failure. This review presents a comprehensive assessment of FGM research up to 2009. It covers design principles, 6 major processing routes, mechanical-thermal-fracture behavior, and modeling approaches. Experimental data indicate that 7-layer ZrO_2/Ni FGMs reduce peak thermal stress by 70% compared to bi-layer systems under $\Delta T=1000^\circ\text{C}$. TiC/steel FGMs show hardness gradient from 1800 HV to 400 HV and 3x wear improvement. Applications span aerospace TBCs, biomedical implants, cutting tools, and electronic packaging. Current limitations include manufacturing cost, residual stress, and lack of design codes. Future directions include nano-FGMs, bio-inspired gradients, and additive manufacturing of FGMs.

Keywords: Functionally graded materials; Thermal barrier; Metal-ceramic; Powder metallurgy; Thermal stress; Graded composites

1. Introduction

Conventional laminated composites suffer from abrupt property mismatch at interfaces, leading to delamination, thermal stress concentration and premature failure. To address this, the National Research Institute for Metals, Japan launched a project in 1984 to develop "Functionally Gradient Materials" for the leading edges of space vehicles requiring surface temperature of 1700°C and body temperature of 100°C [1].

An FGM is a material with composition, microstructure and properties that vary continuously or in a stepwise manner with position, optimized for a specific function [2]. FGMs eliminate stress singularities at interfaces. It tailors thermal conductivity, corrosion resistance through thickness and also combines properties of dissimilar materials: e.g. ceramic heat resistance and metal toughness. Japan, USA, Germany and Korea were leading contributors. This review consolidates developments till date [3].

2. Design Principles and Material Systems

Grading Profiles and Volume Fraction Law: The simplest description uses power-law:

$$V_c(x) = \left(\frac{x}{h}\right)^n$$

where n = grading index. $n=1$ linear, $n<1$ ceramic rich, $n>1$ metal rich.

Other profiles are exponential and sigmoid. Sigmoid gives smoother stress distribution [4-5]. FGM Systems are classified as under:

- Metal-Ceramic FGMs: Most studied. Examples: ZrO_2/Ni , $ZrO_2/Ti-6Al-4V$, $Al_2O_3/NiCr$, SiC/Al . For thermal barriers and wear.
- Metal-Metal FGMs: W/Cu for heat sinks, Ti/TiB for aerospace. CTE matching is goal.
- Ceramic-Ceramic FGMs: Al_2O_3/ZrO_2 for cutting tools. Improves toughness of tool.
- Polymer-Ceramic FGMs: $PMMA/Hydroxyapatite$ for bone. Graded porosity 10-70%.
- Porous FGMs: Density gradient for filters scaffolds [6-7].

Table-1: Property Range [2-10]

Material	k (W/mK)	α ($10^{-6}/K$)	E (GPa)	σ (MPa)
YSZ	2.0	10.5	200	300
Ni	90	15.0	210	600
Ti-6Al-4V	7.0	9.0	110	900
Al ₂ O ₃	30	8.0	380	400

3. Processing and Fabrication Techniques

More than 25 processing techniques for functionally graded materials had been reported in literature. The selection of a particular method depends on the geometry of the component, the nature of constituent materials, and the overall manufacturing cost. These techniques can be broadly classified into solid-state, liquid-state, deposition-based, and other novel routes.

In solid-state routes, powder metallurgy is the most widely used approach. In this method, pre-mixed powders of metal and ceramic are stacked in 5 to 20 layers with gradually varying composition, followed by cold compaction and sintering. This technique has achieved relative densities greater than 98% in systems such as Al_2O_3/Cu , but suffers from the drawback of interlayer diffusion during sintering. Spark Plasma Sintering, developed in the 1990s, offers much faster processing with heating rates of 50–100 °C/min and hold times of 5–20 minutes. It has been successfully applied to fabricate $TiC/steel$ FGMs exhibiting a hardness gradient from 400 to 1800 HV with negligible porosity. Hot pressing is another solid-state method primarily used for thin

plates. A 7-layer ZrO_2/Ni FGM fabricated by hot pressing demonstrated good thermal shock resistance, surviving 1000 thermal cycles between 100 °C and 1000 °C [9-11].

Liquid-state routes utilize melting and solidification to achieve grading. Centrifugal casting exploits the density difference between constituents to produce radial gradients and was commercialized in the 1990s by Toyota for Al–SiC engine cylinder liners with a SiC gradient ranging from 0 to 30 vol%. Squeeze casting infiltration involves forcing molten aluminum into a porous Al_2O_3 preform, resulting in strong interfacial bonding. Sedimentation techniques have also been employed to generate particle size gradients within a matrix [8] & [12].

Among deposition and surface routes, plasma spraying has seen the most commercial success. Layered deposition of YSZ and NiCrAlY on turbine blades can produce 500 μm thick FGMs in about 10 minutes, and such coatings have shown thermal shock life nearly three times higher than conventional bi-layer thermal barrier coatings. Laser cladding and the LENS process, developed between 1998 and 2005, enable direct feeding of powders with varying composition to build 3D FGMs with complex geometries, such as Ti/TiC gradients. CVD and PVD techniques are mainly used for thin-film optical FGMs where a refractive index gradient is required [13-14].

Several novel routes were also explored before 2009, including electrophoretic deposition, gel casting, and self-propagating high-temperature synthesis. SHS has been particularly used for TiC/Ni FGMs through combustion synthesis [15].

Despite these advances, the key challenge across all methods remains the control of residual stresses generated during cooling, which can reach 300–500 MPa in the absence of proper grading profile optimization [10].

4. Mechanical, Thermal and Fracture Behavior

The mechanical, thermal and fracture behavior of functionally graded materials has been a major focus of research up to 2009, primarily because of their ability to mitigate property mismatch. One of the key advantages of FGMs lies in the reduction of thermal stresses. Finite element studies by Jin and Noda in 1994 showed that for a temperature difference of $\Delta T = 1000^\circ\text{C}$, the maximum stress in a conventional bi-material joint reached 800 MPa, while in a 10-layer FGM it was reduced to 200 MPa. This demonstrates the effectiveness of gradual property transition in lowering stress concentrations [4] and [16]. In terms of mechanical properties, FGMs fabricated by different routes exhibit significant gradients tailored to application needs. ZrO_2/Ni FGMs produced by powder metallurgy and hot pressing showed a hardness gradient from 1300 HV on the ceramic-rich side to 200 HV on the metal-rich side, with a flexural strength of 580 MPa and the ability to withstand 1000 thermal cycles between 100°C and 1000°C. TiC/steel FGMs fabricated by Spark Plasma Sintering displayed a hardness range of 1800 HV to 450 HV and a flexural strength of 920 MPa. Centrifugally cast $\text{Al}_2\text{O}_3/\text{Al}$ FGMs exhibited a modulus variation from 18 GPa to 70 GPa with a flexural strength of 440 MPa, while W/Cu FGMs processed by powder metallurgy showed hardness decreasing from 400 HV to 80 HV and flexural strength of 650 MPa. These results

confirm that FGMs can effectively combine the high hardness and thermal resistance of ceramics with the ductility and toughness of metals [10-12] and [17]. Fracture and damage behavior in FGMs is also improved due to the graded architecture. The transition zone promotes crack deflection and bridging, which enhances toughness. For instance, $\text{Al}_2\text{O}_3/\text{Ni}$ FGMs reported fracture toughness of $8.5 \text{ MPa}\cdot\text{m}^{1/2}$ compared to $3.5 \text{ MPa}\cdot\text{m}^{1/2}$ for monolithic Al_2O_3 . Similarly, plasma-sprayed FGM thermal barrier coatings exhibited about 40% higher delamination resistance than conventional bi-layer systems [13] & [18]. Under tribological and environmental conditions, FGMs also showed superior performance. TiC/steel FGMs tested at 500°C had a wear rate of $2.1 \times 10^{-5} \text{ mm}^3/\text{Nm}$, nearly three times lower than the $6.8 \times 10^{-5} \text{ mm}^3/\text{Nm}$ observed for plain steel. In oxidation studies, Al_2O_3 -forming FGMs demonstrated a parabolic rate constant approximately ten times lower than that of pure Ni, indicating improved high-temperature stability [10]. Modeling of FGMs before 2010 relied on three main approaches. Micromechanics models such as Mori-Tanaka and self-consistent schemes were used to predict effective elastic and thermal properties. Finite element methods with graded elements in software like ABAQUS and ANSYS became common from 2000 for detailed stress and thermal analysis. Analytical solutions based on 1D heat conduction and elasticity were also employed for initial design and validation [16] & [19].

5. Applications of FGMs

Functionally graded materials had found applications across aerospace, energy, biomedical, manufacturing, and electronics sectors due to their ability to tailor properties through the thickness. In the aerospace and energy industries, FGMs were primarily used for thermal management. GE and Pratt & Whitney tested YSZ/NiCoCrAlY FGM thermal barrier coatings that demonstrated the capability to withstand surface temperatures approximately 200°C higher than conventional bi-layer TBCs. NASA also evaluated C/C to Cu FGMs in 2003 for rocket nozzle liners to manage extreme thermal gradients. In addition, porous ceramic-metal FGMs were being explored for high-efficiency heat exchangers where a combination of thermal conductivity and corrosion resistance was required [14]. In the biomedical field, FGMs addressed the challenge of mismatch between implant and biological tissue. Hydroxyapatite/Titanium FGMs were developed for dental implants, with a bioactive HAp-rich surface for osseointegration and a strong Ti-rich core. The elastic modulus in these implants was graded from 110 GPa to 20 GPa to closely match that of natural bone. Similarly, Ti/TiB FGMs were investigated for orthopedic applications to reduce stress shielding, with a porous surface layer designed to promote bone in-growth [7].

For cutting tools and wear components, FGMs provided a combination of surface hardness and core toughness. Sandvik and Kennametal commercialized WC-Co FGMs in 2004, with surface hardness of 2000 HV grading to 1200 HV in the core, resulting in approximately two times the tool life compared to homogeneous grades. In the automotive sector, Toyota implemented Al-SiC FGMs as cylinder liners in the Estima model during the 1990s, achieving about 50% reduction in wear [20]. In electronics and optical systems, FGMs were used for thermal management and

optical performance. W/Cu FGMs served as heat sinks in IGBT modules, with a coefficient of thermal expansion graded from 6 to $16 \times 10^{-6}/K$ and thermal conductivity around 200 W/mK, enabling better matching to semiconductor devices. In optics, gradient index or GRIN lenses based on FGM principles had been in use in photocopiers since the 1990s to improve imaging quality [17] and [21].

Other emerging applications included ballistic armor, where ceramic-metal FGMs were used to combine the hardness of ceramics with the energy absorption of metals, and smart systems, where piezoelectric FGMs were reported in 2002 for use in sensors and actuators with spatially varying electromechanical response [22].

6. Challenges, Conclusion and Future Scope

Despite significant progress, several challenges limited the widespread adoption of zfunctionally graded materials. The primary issue was cost. Residual stress and warpage during sintering and cooling remained critical problems, often reaching 300-500 MPa and requiring inverse design of the grading profile to minimize distortion. In terms of characterization, there was no standard non-destructive evaluation method to accurately map the composition gradient within a component. Furthermore, a major gap existed in the materials database, particularly regarding long-term creep, fatigue, and environmental degradation data needed for design codes. Joining FGMs to conventional materials also posed difficulties due to CTE mismatch and inter diffusion at the weld interface [3] & [23-24]. FGMs had evolved from a Japanese national research concept initiated in 1984 to limited commercial products in aerospace, automotive, and biomedical sectors. The core benefit demonstrated across studies was the effective mitigation of thermal and mechanical mismatch at interfaces. Experimental data showed that graded structures could reduce peak thermal stress by up to 70% compared to bi-material joints and improve wear life by approximately 3 times in systems such as TiC/steel. Among all fabrication methods, powder metallurgy and plasma spraying emerged as the most mature and commercially viable routes. Metal-ceramic FGMs dominated research and applications due to their relevance for high-temperature environments. However, widespread industrial adoption was still hindered by high manufacturing cost and the complexity of designing optimal grading profiles [10] & [14]. Looking forward, several research directions were identified based on trends. One major area was nano-FGMs, incorporating reinforcements such as CNTs, graphene, and nano- Al_2O_3 to achieve multifunctional gradients. For example, 1 wt% CNT in a polymer FGM in 2005 resulted in a 35% increase in elastic modulus. Another direction was smart and multifunctional FGMs with gradients in piezoelectric, magnetic, or self-healing properties for sensors and actuators. Bio-inspired FGMs that mimic hierarchical structures found in bamboo, bone, and tooth were also proposed to achieve superior damage tolerance. With the advent of additive manufacturing, direct laser fabrication of FGMs was first demonstrated in 2007, enabling 3D components with complex gradients. The concept of green FGMs using natural fiber and polymer gradients for automotive interiors was

gaining attention for sustainability. Finally, computational design approaches using genetic algorithms and finite element methods were being developed to optimize the grading profile for specific loading and thermal conditions [22-27].

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