Journal of Mines, Metals and Fuels, *71(12): 2455-2459; 2023. DOI: 10.18311/jmmf/2023/35892*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

Future of Multifunctional/Multigrade Materials – A Review

V. Bharathi*, B. R. Ramji and G. Shashikumar

B.M.S. College of Engineering, Bengaluru- 560019, Karnataka, India; bharathi.mech@bmsce.ac.in

Abstract

When functions exclude each other, embedding multiple functions in one material system is a basic challenge. To develop a competence system approach for multifunctionality to enable different applications for the improvement of quality of life and to address worldwide challenges, a basic understanding of structure–function relationships is necessary. The first demand for FGM's came from Space shuttles for high-temperature applications. The conventional materials were found inefficient in meeting this requirement. They have a variety of applications like coating, aerospace, automotive, biomaterials, cutting tools etc.; hence an attempt has been made in this research paper to review the futuristic scope of FGM considering their structure, design criteria, properties, functions and manufacturing and experimental methods.

Keywords: *Combinational Structures, Functions and Applications, Multi Graded Materials, Manufacturing Methods*

1.0 Introduction

Multi-functional materials are original and innovative materials with disparities in their structures and compositions for the entire volume. For thermal barrier application, the thermally graded FGM was first manufactured containing a metal-ceramic phase. The compositions and structures of FGMs can be precisely designed and tailored to create specific multifunctional properties[1].

FGM's can be manufactured using various techniques. Figure 1 shows that liquid state methods involve various casting methods along with the infiltration method and Langmuir- Blodgett methods which were found very effective for the manufacturing of precise and continuous gradient bulk FGM. Tap and slip casting methods and Epoxy glass combinations were extensively produced by vertical gravity casting and hand lay-up techniques for automotive applications[2]. Extensive use of bulk FGM's were found in internal combustion engine's heat resistant valves whereas thin FGM coatings found their usage in supersonic and hypersonic planes and functionally graded heated floor systems for thermal protection systems[3].

Mechanical alignment, field-assisted alignment and hybrid types of additive manufacturing methods were discussed in detail to enhance material properties, and feature size complexity. Computationally efficient design tools enabled non-linear behaviours of components and system-level integration of multi-graded materials into a single product[4]. Limitations of various FGM processing methods were highlighted with justifications and practical disadvantages. Centrifugal casting proved to be better for only cylindrical shapes whereas lase deposition was found expensive for bulk FGM's. The infiltration method was proved to be difficult to regulate whereas additive manufacturing methods demanded secondary finishing operations. Proper control methods exhibited the predesigned property gradient with more than 90% accuracy and the same was justified with SEM pictures[5]. The invention of numerous mathematical models, related theories and the latest methodologies, made modifications possible at unit cell levels within the microstructure. This

---

**Author for correspondence*

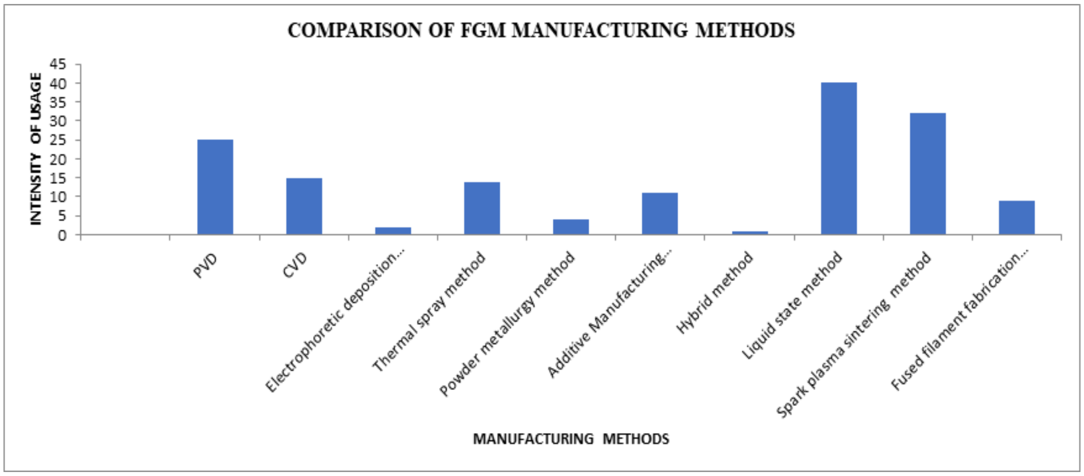

Figure 1. FGM manufacturing methods.

explored the pathway for novel multi-functional cellular composites[6].

Numerous material science algorithms were developed to address the modelling and computational challenges of FGMs[7]. FGM's were investigated for characterization of their lattice structures with relative cell size, density and multi-morphology grading. Triple-surface layered sheet-based lattices were employed for this purpose. Numerical simulations for cell size grading, exhibited higher Young's moduli values while testing along one perpendicular direction than the parallel and other perpendicular direction. The correlation between lattice deformation parallel to hybridization direction in both theory and practical situations was found different. According to the literature, always the deformation was initiated at the interface of different lattices. The same effects were substantiated with the finite element analysis[8].

Crack and fatigue behaviour of FGM's were addressed thoroughly by considering responses of dynamic fracture behaviour of FGM. The impact of stress concentration at the crack-tip, dynamic stress intensity factors and crack growth were discussed in detail to give an impetus to the successful implementation of FGM designs[9]. Investigations were carried out to state the basic concepts, of FGM, classification, properties, manufacturing methods, potential challenges, and diverse applications. Powder metallurgy routed FGM was taken for a case study to justify its characterization through relative density, optical microscopy and hardness[10].

Investigations presented the characterization of graded metallic specimens produced using laser powder bed fusion. Specifically, the work exhibited the material selection criteria to manipulate the chemical composition of iron-based alloys at the element-wise level. A flexible multi-material LPBF platform with continuous Mn variation was achieved by mixing AISI 316L powder with Fe35Mn[11]. Development cycles for multi-materials got shortened due to advanced virtual material design and fabrication schemes[12]. Development of multifunctional polyvalence materials was investigated using materials responsive to temperature, stress and light and shape memory alloys[13].

Investigations highlighted the range of additive manufactured polymer-based, metal-ceramic, and metal-metal applications along with merits and difficulties for multi-graded structures[14].

Dry powder printing and shape deposition manufacturing techniques were addressed in preparing multi-graded materials. Various challenges and future trends like data processing, contamination bonding, process interruption and hybrid and multi-axes systems were discussed to give an impetus for the future of multi-functional materials[15].

The investigations revealed that multi-graded materials were manufactured using the LPBF technique for metal with metal/polymer/glass or ceramic combinations. Recycling, powder cross-contamination, data preparation, process simulation, thermodynamic calculation and the development of power feeding systems proved very critical and difficult to resolve. Various multi-functional materials produced through LPBF equipment were used to construct the structures with interlayer or intralayer printing by modifying the powder feeding systems. But still, low efficiency and powder cross-contamination remain challenges to address[16].

Different gradient types of FGM's were discussed for different applications such as equal channel angular pressing, crash boxes, thick wall pressure vessels etc. Current applications in optoelectronics, biomedical engineering and submarine were also featured[17].

Another recent/latest FGM application is a biomedical segment where functionally graded prosthesis joints showed an increase in adhesive strength with a reduction in pain. However, modern applications may demand material properties in both axial and thickness directions which are of utmost consideration for FG materials. Therefore, such smart bidirectional functionally gradient materials are developed using laser metal deposition-based additive manufacturing technique[3].

Though there is a visible enhancement in the field of applications of FGMs, a few critical challenges still need to be addressed. A strong database of FGMs needs to be established in terms of parameters and testing. FGM's throw a challenge as fabricating methods are very expensive. The selection of proper FGM is going to be a big challenge for future technology development in the FGM research field[3].

The following Table 1 summarizes a few aspects of FGM's[5].

Table 1. Summary contents of FGM's

<table>
<tr><td colspan="12">A. Combination</td></tr>
<tr><td colspan="3">1. Metal – Metal
• Al – Cu
• Al - Ni
• Ni - Ti</td><td colspan="3">2. Metal – Ceramic
• Al - SiC
• Al - Al2O$_3$
• Ni - ZrO$_2$</td><td colspan="3">3. Ceramic -Ceramic
• SiC – Carbon
• SiC - SiC
• Carbon -Carbon</td><td colspan="3">4. Ceramic –Polymer
• Glass -Epoxy
• Carbon –Epoxy</td></tr>
<tr><td colspan="12">B. States of FGM Processing</td></tr>
<tr><td colspan="4">1. Solid stateprocesses
• Powder
• metallurgy
• Diffusionbonding
• Additive manufacturing</td><td colspan="4">2. Liquid stateprocesses Infiltration
• Centrifugal casting
• Gravity settling</td><td colspan="4">Deposition processes
• Vapour deposition
• Spray deposition
• Laser deposition</td></tr>
<tr><td colspan="12">C. Main FGM Dimension</td></tr>
<tr><td colspan="6">1. Thin FGMs (sub-mm range)
• PVD
• CVD
• Thermal spray
• Laser cladding</td><td colspan="6">2. Thick/Bulk FGMs (mmrange)
• Powder metallurgy
• Centrifugaltechniques
• SFF techniques
• Gravity settling</td></tr>
<tr><td colspan="12">D. FGMs Gradation Process</td></tr>
<tr><td colspan="6">Constructive-based processes
• Powder sintering processes
• Vapour deposition processes
• Additive manufacturing</td><td colspan="6">Transport-based processes
• Mass transport process
• Settling and centrifugal process
• Thermal process</td></tr>
</table>

E. Complexity of FGM Product Shape		
1. High complexity	2. Moderate complexity	3. Low
• Solid free-form technique • Thermal and plasma spray forming • Vapour deposition	• Infiltration • Sheet lamination • Laser deposition	• complexity(i). Centrifugalcasting • Centrifugalslurry • Powdermetallurgy

F. Residual Stress due to FGM Production Process	
1. Low • Centrifugal casting • Powder metallurgy • Centrifugal slurry • Infiltration processes	2. High • Vapor deposition • SFF techniques • Laser • Thermal spraying

G. Specific Energy Consumption of FGMs Processes		
1. Low SEC	2. Moderate SEC	3. High SEC
• Centrifugal casting • Centrifugal slurry • Gravity settling	• Powder metallurgy • Vapour deposition • Diffusionbonding	• Thermal andplasma sprayforming • Solid free-formtechnique • Laser cladding

H. FGM Cost of Manufacturing		
1. High cost	2. Moderate cost	3. Low cost
• AM and SFF techniques • Laser cladding • Vapour deposition	• Centrifugalslurry • Powder • metallurgy • Diffusionbonding	• Centrifugal casting • Sheet lamination • Infiltration

I. Areas of FGM Application						
Aerospace	Automotive	Biomaterial	Defence	Nuclear reactors	Smart structures	Sports equipment
Spaceshuttle	Flywheels	Prosthetic devices	Armoured vehicles	Steam generator	Piezo-electric shaft	Tennisrackets

2.0 Conclusion

FGM has many positive points in engineering, industrial and medical applications. They are advantageous as they do not have interlayer overlap and stress concentration but need to be addressed in terms of low manufacturing cost. The durability of these materials is also high and has abundant applications in diverse areas[2]. FGM's can be manufactured for specific composition, microstructure, and porosity levels, for various scales and dimensions, for the construct and the transport gradation process with continuous and discontinuous structures. Product complexity, gradient and residual stress formation can be controlled through solid and liquid deposition processes[5]. Hence in the future FGM's will contribute to typical aerospace, marine, medical and atomic energy applications.

3.0 References

1. Li Y, Feng Z, Hao L, Huang L, Xin C, Wang Y, Bilotti E, Essa K, Zhang H, Li Z, Yan F, Peijs T. A review on functionally graded materials and structures via additive manufacturing: From multi-scale design to versatile functional properties. Advanced Materials Technologies. 2020; 1-32. https://doi.org/10.1002/admt.201900981
2. Hassan AF, Abood AM, Khalaf HI, Farouq W, Khazal H. A review of functionally graded materials including their manufacture and applications. International Journal of Mechanical Engineering. 2022; 7: 744-55.
3. Bhavar V, Kattire P, Thakare S, Patil S and Singh RKP. A review of Functionally Gradient Materials (FGMs) and their applications. IOP Conf Series: Materials Science and Engineering 229. 2017; 1-9. https://doi.org/10.1088/1757-899X/229/1/012021
4. Zheng X, Williams C, Spadaccini CM, Shea K. Perspectives on multi-material additive manufacturing. Journal of Materials Research. 2021; 36:3549–57. https://doi.org/10.1557/s43578-021-00388-y
5. 5. El-Galy IM, Saleh BI, Ahmed MH. Functionally graded materials classifications anddevelopment trends from an industrial point of view. SN Applied Sciences. 2019; 1(11):1-23. https://doi.org/10.1007/s42452-019-1413-4
6. Cadman JE, Zhou S, Chen Y, Li Q. On the design of multi-functional microstructural materials. Journal of Materials Science. 2013; 48:51–66. https://doi.org/10.1007/s10853- 012-6643-4
7. Panchal Y, Ponappa K. Functionally graded materials: A review of computationalmaterials science algorithms, production techniques, and their biomedical applications.Institution of Mechanical Engineers. 2022; 236(22).https://doi.org/10.1177/09544062221109261
8. Al-Ketan O, Dong-Wook L, Abu Al-Rub. Functionally graded and multi-morphology sheet TPMS lattices: Design, manufacturing, and mechanical properties. Journal of the Mechanical Behaviour of Biomedical Material. 2020; 102:1-17. https://doi.org/10.1016/j.jmbbm.2019.103520 PMid:31877523
9. Bhandari M, Purohit K. Dynamic fracture analysis of functionally graded material structures – A critical review. Composites Part C: Open Access. 2022; 7:1-8. https://doi.org/10.1016/j.jcomc.2021.100227
10. Pasha A, Rajaprakash BM. Functionally Graded Materials (FGM) fabrication and its potential challenges and applications. Material Today Proceedings. 2022; 52(3):413-8. https://doi.org/10.1016/j.matpr.2021.09.077
11. Demir AG, Kim J, Caltanissetta F, Hart AJ, Tasan CC, Previtali B, Colosimo BM. Enabling multi-material gradient structure in laser powder bed fusion. Journal of Materials Processing Technology. 2022; 301. https://doi.org/10.1016/j.jmatprotec.2021.117439
12. Lendlein A, Trask RS. Multifunctional materials: concepts, function-structure relationships, knowledge-based design, translational materials research. Journal of Multifunctional Materials. 2018; 1:1-6. https://doi.org/10.1088/2399-7532/aada7b
13. Ferreira BL, Novoa PRO, Marques AT. Multifunctional material systems: A state-of-the- art review. Journal of Composite Structures. 2016; 151: 3-35. https://doi.org/10.1016/j.compstruct.2016.01.028
14. Bandyopadhyay A, Heer B. Additive manufacturing of multi-material structures. Materials Science and Engineering. 2018; 129: 1-16. https://doi.org/10.1016/j.mser.2018.04.001
15. Vaezi M, Chianrabutra S, Mellor B, Yang S. Multiple material additive manufacturing - Part 1: A review. Virtual and Physical Prototyping. 2013; 8:19-50. https://doi.org/10.1080/17452759.2013.778175
16. Wang D, Liu L, Deng G, Deng C, Bai Y, Yang Y, Wu W, Chen J, Liu Y, Wang Y, Lin X, Han C. Recent progress on additive manufacturing of multi-material structures with laser powder bed fusion. Virtual and Physical Prototyping. 2022; 17:329-65. https://doi.org/10.1080/17452759.2022.2028343
17. Sharma NK, Bhandari M, Ashirvad. Applications of Functionally Graded Materials (FGMs). International Journal of Engineering Research and Technology. 2018; 334-9.