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A review of functionally graded materials including their manufacture and applications

Abdulkareem F. Hassan, Ahmed M. Abood, Hassanein I. Khalaf, Wafaa Farouq, Haider Khazal*

Department of Mechanical Engineering, College of Engineering, University of Basrah

Abstract

The concept of functionally graded composite materials for use in engineering was first conceived in the early 1980s when investigators were faced with the need for a type of composite material capable of resisting a very high temperature in the space plane. The conventional composites were tested but they proved to be inadequate. Therefore, FGMs have many different applications in several industries including aerospace, biomaterials, automotive, coating, cutting tools etc. As a result of this importance and application benefit, the current research lists manufacturing methods as well as experimental methods and applications of functionally graduated materials in fracture problems.

Keywords: Functionally graded materials, Manufacturing processes, Applications, Fracture

1. Introduction

In order to meet cryogenic and ultra-high temperature requirements, functionally graded materials (FGMs) were developed. Early research focused on strength, flexibility, and fatigue resistance. This aim is most effectively met by assembling different materials that have those favorable characteristics, thus avoiding the adverse effects of stress concentration and residual stress in the discrete interface (Figure 1). It has been shown that gradual changes in material properties can contribute to efficiency by reducing failures and preserving the intended benefits of fusing different materials [1]. In nature, functionally graded materials can be found in bones, teeth, wood, and bamboo [2].

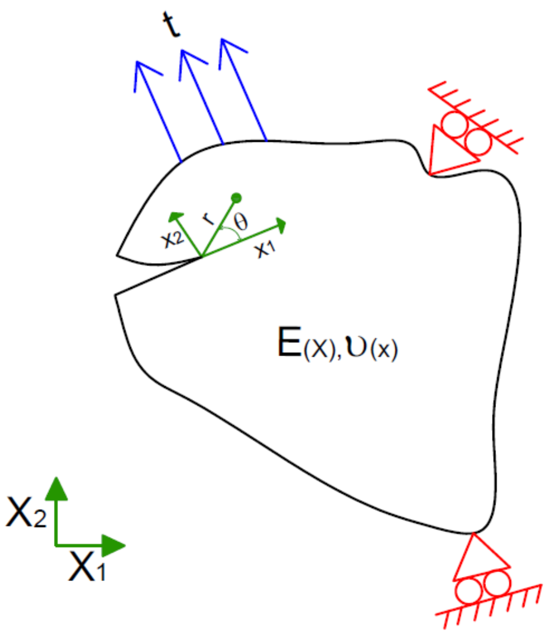

Figure 1. Spatial variation in FGMs

2. Manufacturing of FGMs:

The manufacturing methods of FGMs were developed according to the applications and the desired specifications. Table.1 illustrated some of the production technique and the areas of applications. Good details can be depicted in [3].

Table.1 illustrated some of the production technique and the areas of applications

Manufacturing technique	Area of use	Advantages	publication
1-Deposition based method a- Vapour deposition method 1- Physical vapour deposition (PVD)	Aerospace, automotive	Produced very thin films, environmentally friendly	[18], [57], [58], [59], [64], [76], [80], [93], [102], [107], [108], [112], [116], [117], [129], [130], [131], [141], [142], [143], [144], [169], [173], [174]
2- Chemical vapour deposition method (CVD)	Semiconductor applications	High-quality solid materials, smooth thin films	[7], [10], [14], [40], [44], [47], [54], [61], [73], [78], [84], [98], [134], [164],[192]
b- Electrophoretic deposition method	Coating (nm-mm), infiltration and textured materials	Process equipment is simple, easy to operate, easy to control the accuracy, low coast	[3], [42]
c- Thermal spray method	Surface coating with thin dimensions	Protect the surface against corrosion, wear, thermal and electrical isolation	[32], [81], [94], [95], [103], [118], [132], [145], [162], [175], [176], [177], [178], [179]
2- Solid state method a- Powder metallurgy method	Bioengineering, aerospace, brakes, heat resistant, marine, nuclear industry, biomedical, load bearings, automotive, thermal barriers, electrical contact, high temperature applications, integrated circuits substrates	Producing bulk FGM with discontinuous gradient properties	[1], [2], [15], [23]
b- Additive manufacturing method 1- Laser based a- Selective laser sintering/melting b- Direct energy deposition 2- Stereolithography process	Architecture, medical, robots, automotive, space, energy, sports applications	Good quality and dimensional accuracy	[11], [19], [41], [111], [104], [153], [170]
3- Material jetting process	Medical, dental	Limited materials like polymers and waxes	[16], [29], [123]
4- Fused deposition method	3-D FG alumina ($AL_{2-}O_3$)/ZrO_3	Smooth gradient properties	[124]
3- Hybrid method with additive manufacturing method a- Wire and arc additive method	Some structures like excavator arms , ribs	Produced graded structure with large components at low cost and small production period	[154]
b- Friction stir additive method	Aerospace and defense applications	Cerate much large parts needs post-machining to correct dimensions	[17], [27], [39], [46], [90], [91], [92], [126], [128], [136], [139], [140], [161], [171], [172]
4- Liquid state method includes (centrifugal, force, pressurization, mixed power, sintered-casting, reactive) method	Tubes with gradient properties, Nano-scale FGM	Produce bulk FGM with continuous gradient	[27], [74]

a- Tap casting method	Integrated circuits, multi-layer structures used in integrated circuits, multi-layer condenser	(50-1000μm) tin FGM	[28], [66], [71], [72], [77], [82], [83], [96], [97], [109], [110],[119], [133], [137], [146], [147], [148], [149],[163], [181], [182], [183], [191]
b- Slip casting method	Sealing and conducting component for high-intensity discharge lamps	Produced complex shape of FGM with continuous gradient	[70]
c- Infiltration method	Interlayer for joining ceramics to metal	It can be performed with or without pressure	[27], [34], [74], [114], [123], [124], [136], [154]
d- Langmuir-Blodgett method	Active layer or passive insulator in electronic applications	Uniform film materials with high precision	[26], [85], [105], [187]
5- spark plasma sintering (SPS) method	Different industrial applications	Minimizing of residual stress and the effect of size and shape	[21], [24], [25], [31], [34], [35], [36], [37], [38], [43], [45], [51], [52], [62], [65], [70] ,[79], [105], [106], [114], [115], [125], [137], [138], [155], [156], [157], [158], [159], [160], [169], [179]
6- fused filament fabrication process	multi-material structures	The possibility to manufacture complex geometry materials	[15], [23], [42], [61], [102], [103], [104], [153], [170]

3. Applications of functionally graded materials:

Functionally graded materials are suitable for applications requiring conflicting properties in the same part such as high hardness versus high ductility. Therefore, FGMs have many different applications in several industries including aerospace, biomaterials, automotive, coating, cutting tools etc.Table2. Shows some of these applications:

Table2. Some of industrial uses of FGMs

FGM system	Process	Application
Al_2O_3/Al alloy, SiC-C, C-C, WC-Co, Be-Al, TiAl-SiC, Al_2O_3-Lanthanum Hexaaluminate(LHA)	Hot-pressing method	Aerospace applications
Al_2O_3/Al_2TiO_5, Al-SiC, Al-Al_2O_3, Sic-SiC, Al-C, E-glass-epoxy and Al-Mg_2Si	Powder metallurgy	Automotive applications
Cu-ZrO_2/Cu-C-MoS_2-ZrO_2, TiCN-WC/Co, WC/Co	Liquid phase sintering	Machinery and equipment applications
Ti/HA, Al_2O_3/Zro_2, Al_2O_3-SiC-zrO_2, SS316L-HA, ZrO_2	Powder metallurgy	Biomedical applications
TiB_2-Ti, Al-SiC, ZrO-Zr_2CN/Si_3N_4, Al_2o_3-ZrO_2	Powder metallurgy	Defense applications
Al-Mg_2Si, Ni-ZrO_2	Thermal spraying	Energy applications
SiC with Al2O3 and Yb2O3	spark plasma sintering (SPS) method	Different of industrial functions

Figure 2 clears the classification of FGMs applications. In addition, the application of FGMs sometimes are depended on types of graded of material preparties in stepwise or in continues type (Figure 3).

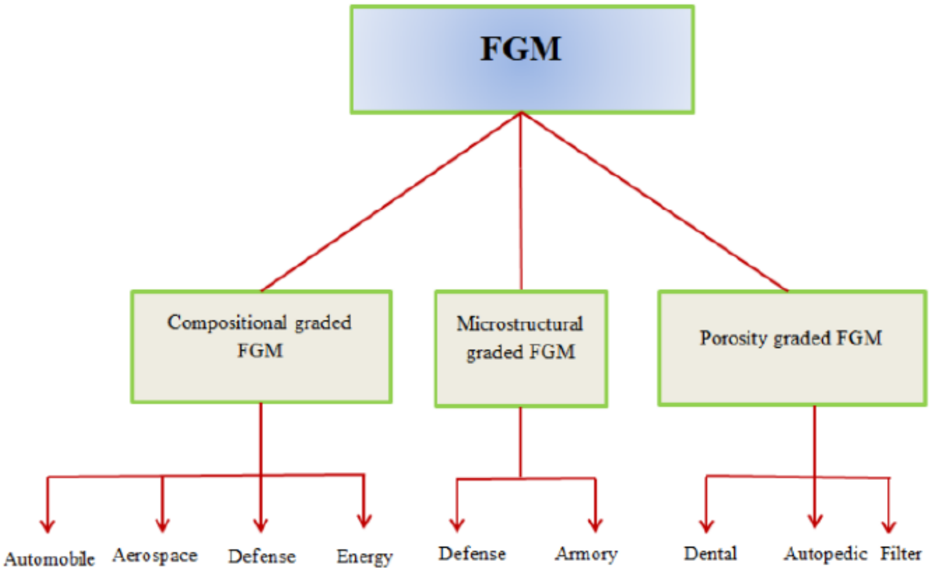

Figure 2. The classification of FGMs applications

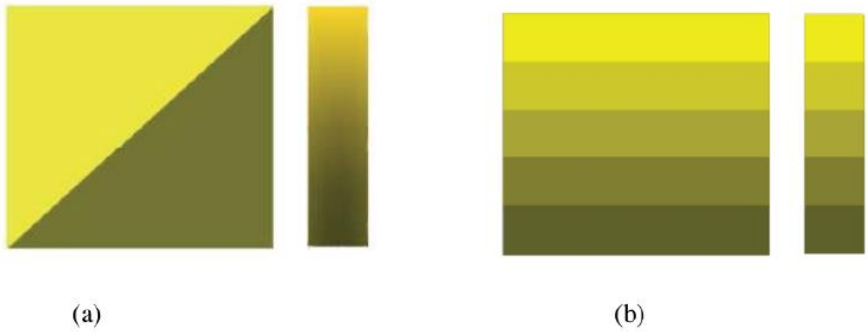

Figure 2. Schematic of material gradient (a) continues, (b) stepwise

4. Experimental investigation of fracture in functionally graded materials:

Fracture of functionally graded materials had been studied by many researchers to understand the influence of gradient in properties on the failure behavior of this important type of composite materials. Analytical approaches exhibit difficulties in solving FGMs problem because the complexity due to the spatial gradient. Therefore, the numerical solution of fracture problem occupied a large area in this field. The experimental investigation of fracture parameters was playing a significant role in analysis of FGMs. This paper review experiments that have been performed on FGMs and describes the principal of the digital image correlation method. Different types of FGMs were investigated over duration about 30 years Table 3 clarify some researches that were studied the fracture in FGMs and the composite that were used in these studies. Additionally, there are many numerical studies that deal with the behavior of functionally graded materials under different mechanical and thermal load. An example of these studies references [122], [152], [167], [188], [189].

Table3 FGMs used in study of fracture mechanics

Publications	FGM	process
[21]	Epoxy-glass	Vertical gravity casting
[24]	Epoxy-glass	Vertical gravity casting
[25]	Epoxy-glass	Vertical gravity casting
[31]	Epoxy glass	Vertical gravity casting
[51]	Carbon monoxide co-polymer	Irradiation with UV lights
[35]	Epoxy-glass	Mixed under vacuum
[36]	Flat Nimonic plate with 100µm NiCoCrAlY bond coat and 250µm ZrO_2	Physical vapor deposition
[45]	Epoxy-glass	Vertical gravity casting

[52]	Epoxy-glass	Vertical gravity casting
[37]	AlSi-based coated Al-alloy	Laser cladding technique
[62]	ZrO_2/NiCr	Powder metallurgy
[138]	Ti6Al4V/TiC	Direct laser deposition
[106]	Epoxy-glass	Vertical casting
[155]	Epoxy-glass	Hand lay-up
[156]	Polyester polymer with long glass fiber	Hand lay-up
[157]	Ti-TiB	Powder metallurgy
[168]	Epoxy-glass	Hand lay-up

Conclusion:

Functionally graded material generates many positive points in engineering, industrial and medical applications as a result of the following properties:

1- It does not contain interlayer overlaps as found in composite materials.
2- The stress concentration in the layers is not present in these materials because they are manufactured gradually.
3- The age of the machine or device in which these graded materials are used increases as the functional graded materials play a role that cannot be played by a metal or other composite material.
4- There are difficulties in manufacturing, and the best manufacturing method is the central method, and the easiest one is the hand lay-up method.
5- The applications of graded materials cannot be counted due to their abundance, as they have been used in medical, military, aerospace, and many different engineering applications.

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