Study on a revolutionary composite material: functionally graded material (FGM)

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Abstract: Functionally graded material (FGM) is a class of advanced materials which have dual phase composition with uniformly varying material properties in thickness direction. This paper describes the basic concepts, rules for assessment of material properties gradation, processing techniques, classification, application and design aspect of FGM. Based on analysis the present scenario of FGM is discussed and future research direction is suggested.

1. INTRODUCTION

With the introduction of new theories, new methods and new experimental techniques along with interdisciplinary interaction in recent years, material science development has taken place [1] through invention of new advanced materials. One of the reasons of this development can be contributed to urgent requirement of material fulfilling the practical problems. FGM is a new composite material which has ‘high performance’ and ‘multi-functional role’ [2] that make it suitable to be used in many applications like new generation space shuttle, wind tunnel blades, fuel pellets, armour plates, electronics, optoelectronics, automobiles, naval application dental implant, knee replacement etc. FGM is a microscopically inhomogeneous material formed by blending two or more distinct materials in a regular/uniform manner. Continuous change in microstructure of FGM differentiates it from other traditional composite materials which undergo failure through a process called delamination under extreme thermal and mechanical loading. These are tailored by varying the constituent materials spatially in such a way to obtain the desired mechanical properties i.e., Young’s modulus, Poisson’s ratio, shear modulus and material density in preferred direction. A very common example of FGM is ceramic-metal composites where ceramic phase has good corrosion and thermal resistance and metallic phase gives superior fracture toughness and weldability.

2. THE CONCEPT OF FGM

![Figure 1. schematic view of material gradation](image-url)
There are two types of compositions which can be manufactured in case of FGM, uniformly varying continuous composition as shown in Figure 1(a) and stepwise composition as shown in Figure 1(b). In case of uniformly varying composition the variation in microstructure occurs continuously with position. On the contrary, in case of step wise, microstructure changes in stepwise manner, creating a multilayered composition with interface existing between distinct layers. Figure 1 represents the schematic view of both types of composition relative to FGM.

3. RULES FOR GRADATION OF MATERIAL

A FGM is made by varying volume fraction of the materials in some specific gradient. So, the material properties in FGM are uniformly varying in a direction [3]. For numerical investigations these spatially varying properties need to be modelled or quantified. Some rules used for this purpose are listed here.

3.1 Power law:

It is widest used method among researchers for stress analysis of FGM structures or laminates having FGM layer. The effective property of FGM is found from volume weighted average of the constituent materials. This gradation scheme was first introduced by Wakashima [4]. Further this law has gained popularity for modelling and analysis of FG sandwich structures like plates, beams and shells. This law is governed by linear rule of mixture and properties vary across the dimensions of

The equation defines the properties of material \( z \) at any depth \( z \) for single layer FG plate.

\[
P(z) = P_m + (P_c - P_m) V(z)
\]

The volume fraction function \( V(z) \) for single layer FG structure (Type A)

\[
V(z) = \left( \frac{z - h_0}{h_1 - h_0} \right)^p \quad \text{for} \quad z \in [-h/2, h/2]
\]

The volume fraction function \( V(z) \) for a three-layered sandwich plate with FG face sheets (Type B)

\[
V(z) = \left( \frac{z - h_0}{h_1 - h_0} \right)^p \quad \text{for} \quad z \in [h_0, h_1]
\]

\[
V(z) = 1 \quad \text{for} \quad z \in [h_1, h_2]
\]

\[
V(z) = \left( \frac{z - h_2}{h_3 - h_2} \right)^p \quad \text{for} \quad z \in [h_2, h_3]
\]

The volume fraction function \( V(z) \) for a three-layered sandwich plate with FG core (Type C)

\[
V(z) = 0 \quad \text{for} \quad z \in [h_0, h_1]
\]

\[
V(z) = \left( \frac{z - h_2}{h_3 - h_2} \right)^p \quad \text{for} \quad z \in [h_1, h_2]
\]

\[
V(z) = 1 \quad \text{for} \quad z \in [h_2, h_3]
\]

The above equation defines the properties of material \( z \) at any depth \( z \) for single layer FG plate. \( P_c \) denotes properties (E,G,\( \mu \),\( \rho \)) of ceramic phase \( P_m \) denotes properties (E,G,\( \mu \),\( \rho \)) of metallic phase, \( p \) is the power law index governing the way of variation of material properties, \( h \) is total thickness. Figure 2 presents the lamination schemes for the above discussed three types of sandwich plates (Type A, Type B and Type C) with their coordinate system. Figure 3 represents the variation of Young’s modulus along the thickness of sandwich plates for different values of power law index \( p \).

3.2 Exponential Law:

This law is more commonly used in fracture studies of FGM plates and beams. It is given by kim and Paulino [5] and Zhang et al.[6] The variation of properties of single layer FG plates or beams across thickness is given as

\[
(z) = P_m \exp \left[ \log \left( \frac{P_c P_m}{V_c(z)} \right) \right] z \in [-h/2, h/2]
\]

Here value of \( v(z) \) can be calculated from power law as discussed above.
3.3 Sigmoid law:
The sigmoid law for estimation of material property variation is specifically used for bilayer plates. The sigmoid function comprises of a combination of two power law functions. It was developed by Chung and Chi [7] for reducing stress intensity factor in cracked structures. The application of single power law in layered FG plate results to discontinuity of stresses at the junction of the layers, two different power law functions are used to govern the distribution of material properties. The first power law is used in upper layer from top surface to neutral axis ($z=-h/2$ to 0) and the second power law is used in bottom from neutral axis to bottom surface ($z=0$ to $h/2$). Figure 3 shows the variation of Young’s modulus in the thickness direction for FG sandwich plates.

The anti-symmetric power law function is given as

\[
P(z) = P_m + (P_e - P_m) \left[ 1 + \left( \frac{z}{h} \right)^{\frac{1}{3}} \right] \quad \text{for } z \in [-h/2, 0]
\]
\[
P(z) = P_m + (P_e - P_m) \left[ 1 + \left( \frac{z}{h} \right)^{\frac{1}{3}} \right] \quad \text{for } z \in [0, h/2]
\]

The symmetric power law function is given as

\[
P(z) = P_e + (P_m - P_e) \left( \frac{2z}{h} \right)^{\frac{1}{3}} \quad \text{for } z \in [-h/2, 0]
\]
\[
P(z) = P_e + (P_m - P_e) \left( \frac{2z}{h} \right)^{\frac{1}{3}} \quad \text{for } z \in [0, h/2]
\]
4. FGM CLASSIFICATION AND APPLICATIONS

FGM is classified according to a variety of criteria [8]. According to constituent materials, FGM is divided into ceramic/ceramic, metal/ceramic, ceramic/plastic etc. According to usage of FGM, connection type FGM (connecting layer between two different materials with distinct properties)
coating type (forming a coating layer in matrix material) and according to different application areas can be divided into biology FGM, chemical Engineering FGM, heat resisting FGM, Electronic Engineering FGM etc. Table 1 is given below listing different types of FGM along with their applications

Table 1. List of types of FGM with their applications

| Sl.No. | FGM type | Requirements | Application |
|--------|----------|--------------|-------------|
| 1      | SiC-SiC  | Corrosion resistance and hardness | Combustion chambers |
| 2      | Al-SiC   | Hardness and toughness | Combustion chambers |
| 3      | SiCw/Al-alloy | Thermal resistance and chemical resistance | CNG storage cylinders, Diesel Engine pistons |
| 4      | E-glass/epoxy | Hardness and damping properties | Brake rotors, Leaf springs |
| 5      | Al-SiC   | Hardness and damping properties | Flywheels, racing car brakes |
| 6      | Carbon and glass fibres | Propulsion shaft |
| 7      | Al2O3/Al-alloy | Good thermal and corrosive resistance | Rocket nozzle, Wings, Rotary launchers, Engine casing |
| 8      | TiAl-SiCfibres | Composite piping system, Scuba diving cylinders |
| 9      | Carbon/Epoxy | Lightweight and damping properties | Helicopter components viz. Rotor drive shaft, mast mount, Main rotor blades |
| 10     | SiCw/6061 | Hardness and toughness | Racing bicycle frame, Racing vehicle frame |
| 11     | Al-alloy/CNT | Light weight and high stiffness | Artificial ligaments, MRI scanner cryogenic tubes, wheelchairs, Hip joint implants, Eyeglass frames, camera tripods, Musical instruments |

5. PROCESSING METHODS

Many researchers proposed several different physical and chemical methods for fabrication of FGM [8]. There are two broad divisions based on layered construction and mass transport [9, 10]. In first division a layer-by-layer construction is done so that the required gradient can be fabricated, advantage being possibility of accommodating unrestricted number of gradients. Meanwhile in the second division the gradients are created by natural transport phenomenon such as the diffusion of atomic species, the flow of fluid or heat conduction. However during the last two decades since the automation technology has been advanced, making the constitutive gradation process technologically and economically feasible. The details of existing and most update processes for fabrication of FGM are discussed below.

5.1 Vapor Deposition technique (VDT):

There are numerous types of vapor deposition techniques(VDT) available including chemical vapor deposition (CVD), physical vapor deposition (CVD), sputter deposition, plasma enhanced chemical vapor deposition etc. In VDT as the name suggest the materials are brought to vapor state which are then condensed/ deposited to solid form through condensation, chemical reaction etc.[9,10] These vapor deposition methods are used to form functionally graded surface coatings. VDT are energy intensive but at the same time produce poisonous gases as by-products[11].
5.2 Powder metallurgy:
Powder metallurgy process is used for producing FGM, have four basic steps(weighing and mixing, stacking, pressing and sintering) [3,12,13,14]. Weighing and mixing constitutes he first phase in which the materials are precisely weighed by instrument and uniformly mixed through V shaped mill/ ball mill, to produce a number of different mixes which vary with respect to proportion of the constituents. In the next step, i.e. stacking, these different mixes are so arranged/stacked in their respective die to produce the predesigned spatial gradient. In the third step the compaction of powder mixes in stack is done to produce geometric form and pressing is usually done at room temperature. The success criteria of this step mainly depends on the compatibility of the powder mixes [15]. In the last step sintering, high pressure and electric energy is used to bring together powder particles. The FGM formed by this method should have stepwise structure. A continuously graded FGM is difficult to obtain by this method, however if centrifugal force is employed a continuously graded FGM can be obtained[16].

5.3 Centrifugal casting (CS):
In CS method molten mass is poured into a rotating mould. Due to rotation centrifugal force is experienced by the molten material in the mould according to their density. Solid particles in the molten mass distribute settle and solidify with respect to their densities and thus a compositional gradient is produced. This method is exclusively used in producing cylinder parts [10].The success of CS method depends on the difference in the densities of solid particles present in the solid mass [17, 18], since a natural process is adopted (centrifugal force and density difference) for creating gradient in composition.

5.4 Solid freeform fabrication method (SFFM)
SFFM is a most precise technology for creating FGM. A information regarding the details of object like shape, size, gradient of materials is generated in the computer and is used by SFFM for producing physical objects same as the information. Through this method maximum material utilization, higher speed of production, high accuracy, production of complex shapes and design, minimization of energy consumption is attained [19]. laser based processes are mostly utilized in SFF [20].

6. FGM DESIGN

The usage of FGM in any application involves defining material combination, material preparation and evaluating stress variation by material properties [21]. A reverse design process is to be adopted for the design of FGM. First determine the application condition (load, temperature, end conditions) and structure of material, and then select the appropriate material combination from FGM design database, after that decide on the variation/gradient of material as well as preparation methods and finally after finalizing the material, apply a suitable mathematical model for calculating stress distribution for determining proposed structure’s ability to withstand the given conditions. Self-developed computer aided software incorporating commonly used mathematical model can be used for the optimal design of FGM structures.

7. CONCLUDING REMARKS

In present paper various aspects of FGM like concept, classification and application, rules for material gradation, processing methods and design has been discussed. The general outcomes from this study areas follows

1. FGM has emerged as a high-performance new material which seems to be highly promising in many application areas. Tailoring of FGM by choosing material combination and the gradation technique should be done very wisely according to application.

2. The assessment of gradation of properties in FGM is very important for analysis part. A number of rules for assessing the material properties were discussed and it can be concluded
that among all the available rules power law is most accurate, simple to use and save computational time.

3. Among all the available processing techniques, powder metallurgy is mostly adopted now a days, however some improvement in techniques is required to get assured distribution of properties throughout the structure.

4. Although FGM was initially developed as high temperature thermal barrier in aerospace application but with deepening of FGM research, FGM was found more efficient than the most of the conventional materials in many application areas, yet the full potential of FGM still needs to be explored. One aspect of FGM is its applicability in medical field like artificial bones, dentistry etc. Researches in this areas should be extended for the benefit of society.

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