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Recent development in modeling and analysis of functionally graded materials and structures

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ABSTRACT

In this article, an extensive review related to the structural response of the functionally graded materials (FGMs) and structures have been presented. These are high technology materials developed by a group scientist in the late 1980's in Japan. The emphasis has been made here, to present the structural characteristics of FGMs plates/shells under thermo-electro-mechanical loadings under various boundary and environmental conditions. This paper also provides an overview of different fabrication procedures and the future research directions which is required to implement these materials in the design and analysis appropriately. The expected outcome of present review can be treated as milestone for future studies in the area of high technology materials and structures, and would be definitely advantageous for the researchers, scientists, and designers working in this field.

Contents

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Nomenclature

FGMs	functionally graded materials
VDT	vapor deposition technique
PM	powder metallurgy
CVD	chemical vapor deposition
PVD	physical vapor deposition
CS	centrifugal casting
SFFM	solid freeform fabrication method
P(z)	Effective material properties
P_t	material properties at top surface
P_b	material properties at bottom surface
V_f	volume fraction
h	thickness of the plate
n	volume fraction exponent
CLPT	classical plate theory
FSDT	first order shear deformation theory
SSDT	second order shear deformation theory
TSDT	third order shear deformation theory
HSDT	higher-order shear deformable theory
MLPG	meshless local Petrov–Galerkin
IHZZT	inverse hyperbolic zigzag theory
FOPT	first-order perturbation technique
u,v,w	displacement field variables
$u_{0,}v_0$	in-plane displacement of the point on reference plane
w_0	transverse displacements of the point on reference plane
$\theta_x,\theta_y\varphi_x\varphi_y$	rotations of the normal to the plate's middle surface
PDEs	partial differential equations
NURBS	non-uniform rational basis spline
DOF	degree of Freedom

1. Introduction

Great performance achievements are already well in hand for the class of materials called composites, in which one type of hybrid material is functionally graded materials (FGMs). In the last of 20th century, virtually every facet of the familiar world, from bicycle to spacecraft, clothing to construction, would be intensely changed by new class of materials. High performance materials like FGMs also make possible some of the century's most astonishing technological achievements in the field of biomedical, optoelectronics, spacecraft, chemical, mechanical, and other engineering applications.

Functionally graded materials (FGMs) are high performance, microscopically inhomogeneous materials with engineered gradients of composition and structure with specific properties in the preferred orientation [1,2]. Continuous changes in their microstructure, FGMs make a distinction from other traditional composite materials which fail through a process called delamination in the extreme mechanical and thermal loadings [3,4]. The desired mechanical properties of FGMs i.e. Young's modulus, shear modulus, Poisson's ratio, and material density can be obtained in a preferred direction through the variation of volume fractions of the constituent materials spatially. Fig. 1 shows the variation of material properties in conventional composite and FGMs. This high technology material provides excellent heat and corrosion resistance capability, and being able to withstand ultra-high temperature gradients [2,3]. The very common available FGMs are ceramic–metal composites, where the ceramic part has good thermal and corrosion resistance capability and metallic part provides superior fracture toughness and weldability [5]. A continuously graded microstructure with metal/ceramic constituents is represented in Fig. 2.

Gururaja et al. [6] and Howard [7] have found that the FGM can act as an interface layer to connect two incompatible material to enhance the bond strength, remove stress concentration, provide multifunctionality, ability to control deformation, dynamic response, wear, corrosion, etc. During the last three decades researchers have regularly demonstrated that FGMs helps to decrease in the magnitude of the peak thermal stresses [8–12], eliminates the stress concentrations at the interface layers and free edges in laminated composites [13–15]. FGM also improves the fracture toughness of brittle ceramics by the introduction of a metallic phase that deforms plastically [16,17].

2. Processing techniques of functionally graded materials (FGM)

There are several different physical and chemical methods available for the fabrication of FGMs depending on type of materials, application and accessible amenities. The processing methods of FGMs can be classified into two broad categories based on constructive processing and mass transport [18,19]. In the first category, the FGM is constructed layer by-layer starting with an apposite distribution in which the gradients are literally constructed in space. The advantage of this technique is to fabricate unrestricted number of gradients. Meanwhile in the second category the gradients within a components are depend on natural transport phenomenon such as the flow of fluid, the diffusion of atomic species, or heat conduction. However advances in automation technology during the last two decades have proffer constitutive gradation processes technologically and economically feasible. The existing and most updated techniques for fabrication of FGMs is given in details and the overview of processing processes is shown in Table 1.

2.1. Vapor deposition technique

There are various types of vapor deposition techniques (VDT) available which includes, sputter deposition, chemical vapor deposition (CVD) and physical vapor deposition (PVD), plasma enhanced chemical vapor deposition etc. In vapor deposition method the materials in a vapor state are condensed through condensation, chemical reaction, or conversion to form a solid material [18,19]. These processes are used to form coatings to change the mechanical, electrical, thermal, optical, corrosion resistance, and wear properties of the substrates. These vapor deposition methods are used to deposit functionally graded surface coatings that give excellent microstructure for thin surface coating. Vapor deposition technique are energy intensive but produce poisonous gases as their by-products [20].

2.2. Powder metallurgy

Powder metallurgy (PM) technique is used to produce functionally graded material [1,21,22] through four basic steps namely: powder preparation, weighing and mixing of powder according to the pre-designed spatial distribution, stacking and ramming of the premixed-powders (forming operations) and finally compacting and forming a solid mass of material (sintering) [23]. Several techniques have been employed for preparation of powder such as through chemical reactions, electrolytic deposition, grinding, pulverization, atomization, centrifugal disintegration, solid-state reduction etc. Powder processing method is focused on the precision in weighing amounts and the dispersion of the mixed powders which influence the structure properties. The forming operation is