A Review on Functionally Graded Annular Disc

Aviral Kumar Jain[1], Santosh Kumar Mishra[2,*]

[1]*MechanicalEngineering,BhilaiInstituteofTechnology,Durg491001, India*
[2]*Mechanical Engineering, Bhilai Institute of Technology, Durg 491001, India*
[1]*aviraljain1992@gmail.com,* [2]*san810@gmail.com*

Abstract

Functionally graded Materials (or also can say, Functionally Gradient materials) are characterized as an anisotropic material whose physical properties varies continuously as the dimensions varies randomly or strategically, to achieve the desired characteristic. The overall properties of the functionally gradient material are different from the properties of any of the individual parent materials which form it. They can be applied to metals, ceramics and organic composites to generate improved components, they are increasingly being considered in industry for various applications to maximize strengths and integrities of many engineered structures. The processing's of FGM is costly, but it is expected the researches carrying in this field for fabrication and processing of such materials will reduce the cost and makes the materials easily available as well as applicable in wide area of applications. The study is mainly focused on comprehensive overview of the various production techniques for manufacturing of functionally graded materials; characterizations, advantages and formulation of FGMs as well as recent developments in this field are presented.

1. Introduction

Many engineering components may be modeled as rotating circular plates or disks. Some examples may be found in the power transmission systems, machining devises, circular saws, microwave or baking ovens, photographic facilities, support tables, turbo-machinery, and flywheel and centrifugal systems. Some of these components (e.g., the clutch or brake disks) may be supported by generally non-uniform elastic foundations that rotate with the assembly. On the other hand, the main advantage of using the functionally graded materials (FGMs) is providing the capability of accurately monitoring changes of the local material properties to optimize the component strength. Therefore, achieving a uniform effective stress to strength ratio in the whole component can be an objective. Depending on the function of the component, it is possible to utilize one-, two- or three-directional distributions of the material properties.

Laminated composites have received a lot of interest in recent days by diversified and potential applications in automotive and aerospace industry due to their strength to weight, stiffness to weight ratio, low fatigue life and toughness and other higher material properties. These are made from two or more constituent materials which have different chemical or physical properties and produced a material having different behaviour from the individual. These are used in buildings, storage tanks, bridges etc. Each layer is laminated in order to get superior material properties. The individual layer has high strength fibres like graphite, glass or silicon carbide and matrix materials like epoxies, polyimides. By varying the thickness of laminas desired properties (strength, wear resistance, stiffness) can be achieved.

Although these materials have superior properties, their major drawback is the weakness of laminated materials. This is known as delamination phenomenon which leads to the failure of the composite structure. Residual stresses are present due to difference in thermal expansion of the matrix and fibre. It is well known that at high temperature the adhesive being chemically unstable and fails to hold the lamination. Sometimes due to fibre breakdown it also prematurely fails.

Functionally Graded Material (FGM) is combination of a ceramic and a metal. A material in which its structure and composition both varies gradually over volume in order to get certain specific properties of the material hence can perform certain functions. The properties of material depend on the spatial position in the structure of material. The effect of inter-laminar stress developed at the laminated composite interfaces due to sudden change of material properties reduced by continuous grading of material properties. Generally microstructural heterogeneity or non-uniformity is introduced in functionally graded material. The main purpose is to increase fracture toughness, increase in strength because ceramics only are brittle in nature.

Brittleness is a great disadvantage for any structural application. These are manufactured by combining both metals and ceramics for use in high temperature applications. Material properties are varies smoothly and continuously in one or many directions so FGMs are inhomogeneous. FGM serves as a thermal barrier capable of withstanding 2000K surface temperature. Fabrication of FGM can be done by different processing such as layer processing, melt processing, particulate processing etc.

FGM has the ability to control shear deformation, corrosion, wear, buckling etc. and also to remove stress concentrations.

The effective material properties of the FGM plate are assumed to be varying continuously along their thickness direction as discussed earlier and are obtained by using a simple power-law distribution or exponential law which counts the volume fraction of each constituent.

1.1. Exponential law

Exponential law of grading FGM states that for a FGM structure of uniform thickness '*h*', the material properties '*P(z)*' at any point located at '*z*' distance from the mid-plane surface is given by:

$$P(z) = P_t e^{\left(-\lambda\left(1-\frac{2z}{h}\right)\right)}, \text{where, } \lambda = \frac{1}{2}\ln\left(\frac{P_t}{P_b}\right)$$

P(z) denotes material property like Young's modulus of elasticity (*E*), shear modulus of elasticity (*G*), Poisson's ratio (v), material density (ρ) of the FGM structure. $P_t$and P_b are the material properties at the top ($z=+h/2$) and bottom ($z=-h/2$) surfaces. λ is the material grading indexes which depend on the design requirements.

1.2Power law

The power-law distribution of a panel considered from the mid-plane reference plane can be written as

$$V_f = \left(\frac{z}{h}+\frac{1}{2}\right)^n$$

where, *n* is the power-law index, $0 \le n \le \infty$. The functionally graded material with two constituents and their properties such as, Young's modulus *E* and the mass density *ρ* have been obtained using the following steps.

$$E = (E_c - E_m)\left(\frac{z}{h}+\frac{1}{2}\right)^n + E_m$$

$$\rho = (\rho_c - \rho_m)\left(\frac{z}{h} + \frac{1}{2}\right)^n + \rho_m$$
$$\vartheta = (\vartheta_c - \vartheta_m)\left(\frac{z}{h} + \frac{1}{2}\right)^n + \vartheta_m$$

1.3 Mori-Tanaka scheme

Mori-Tanaka method of estimation is most applicable for regions with graded microstructure which have well defined continuous matrix phase and randomly distributed spherical particulate phase. This method accounts the effect of elastic fields among neighboring inclusions and its interactions with the constituents.

$$\frac{K_z - K_m}{K_c - K_m} = \frac{V_f^p}{1 + (1 - V_f^p)\left(\frac{K_c - K_m}{K_m + \frac{4}{3}G_m}\right)}$$
$$\frac{G_z - G_m}{G_c - G_m} = \frac{V_f^p}{1 + (1 - V_f^p)\left(\frac{G_c - G_m}{G_m + f_m}\right)}$$
$$f_m = \frac{G_m(9K_m + 8G_m)}{6(K_m + 2G_m)}$$

The effective values of Young's Modulus of elasticity Ez and Poisson's ratio ϑ are calculated based on effective Bulk modulus Kz and shear modulus Gz and are related as,

$$E_z = \frac{9K_z G_z}{3K_z + G_z}$$
$$\vartheta = \frac{3K_z - 2G_z}{2(3K_z + G_z)}$$

The effective heat conductivity kz and coefficient of thermal expansion αz are determined

$$\frac{K_z - K_m}{K_c - K_m} = \frac{V_f^p}{1 + (1 - V_f^p)\left(\frac{K_c - K_m}{3K_m}\right)}$$
$$\frac{\alpha_z - \alpha_m}{\alpha_c - \alpha_m} = \frac{\frac{1}{K_z} - \frac{1}{K_m}}{\frac{1}{K_c} - \frac{1}{K_m}}$$

Where, the volume fraction distribution Vf, is assumed according to power law function p. The subscripts m and c represents the thermo-mechanical properties of metal and ceramic constituents respectively.

1.4.Sigmoidal function

This method is most applicable in layered FGM plates i.e., FGM plate with ceramic at the center and graded to metal on both sides or vice versa. In such cases, if single power law function is used stress concentrations will appear at the interfaces where the material is continuous but changes rapidly.

$$V_{f1} = 1 + \left(\frac{z}{h} - \frac{1}{2}\right)^p \text{ for } 0 \le z \le h/2$$
$$V_{f2} = \left(\frac{z}{h} + \frac{1}{2}\right)^p \text{ for } -h/2 \le z \le 0$$

Further, the effective material properties across the plate thickness is computed using power law function based on rule of mixture by using appropriate volume fraction function across the thickness direction. Also, optimal composition of constituents can be achieved by varying power law parameter.

1.5. Temperature dependent properties

FGMs are mainly designed for structural members to suit high temperature environments. Therefore, the effect of temperature plays a vital role in evaluating the behaviour of FGM.

$$P = P_0\left(\frac{P_1}{T} + 1 + P_1 T + P_2 T^2 + P_3 T^3\right)$$

Where, P0, P1, P2 and P3 are constants in the cubic fit of the material property and temperature. The temperature dependent variation of modulus of elasticity, thermal conductivity and thermal coefficient of expansion are evaluated for ceramics and metals. Thus the effective properties that are dependent on both temperature and position (z) are estimated using simple rule of mixtures and are given by,

$$P_{eff}(z,T) = P_m(T) + [P_c(T) - P_m(T)]V_f$$

Where, V_f is the volume fraction of the ceramic phase evaluated using power law function p and is independent of temperature. The effective material properties can be evaluated for various forms of temperatures across the thickness direction namely, constant, linear and nonlinear variations.

2. Methods of manufacturing FGMs

Several techniques are available to produce functionally graded materials (FGMs).

2.1. Vapor deposition technique

Vapor deposition techniques describe a variety of vacuum deposition methods which can be used to produce thin films on the base materials. All these techniques can be used to produce thin FGMs only. Different types of vapour deposition techniques include physical vapour deposition (PVD) and Chemical vapour deposition (CVD). These are energy intensive and produce poisonous gages as their by-products [3]. Other deposition based techniques which can deposit thin functionally gradient coatings are electron beam deposition (EBD), Ion beam deposition (IBD) and Self propagating high temperature synthesis (SHS) [4]. All above mentioned methods are uneconomical to produce bulk type FGMs.

2.2 Powder metallurgy

Powder metallurgy based technique can be used to produce bulk type FGMs with discontinuous (stepwise) structure. The process is carried out by using steps including weighing and mixing of powder according to the pre-designed spatial distribution as per functional requirement, stacking and ramming of the premixed-powders, and finally sintering [5].

2.3 Centrifugal method

Centrifugal method is capable to produce continuously structured bulk type FGMs. It uses force of gravity through spinning of mould to produce functionally graded materials [6]. Difference in material densities and spinning of mould produces FGMs. There are two disadvantages of this method are this method can produce only cylindrical shaped FGMs and there is limit to which type of gradient can be produced.

2.4 Solid free form fabrication/additive manufacturing (AM) techniques

Solid freeform fabrication (SFF)/Additive manufacturing (AM), also known as 3D printing, is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technology [7]. This tool-less manufacturing method can produce fully dense metallic parts in short time, with high precision. Metal AM processes can be broadly classified into two major groups, - Powder Bed Fusion based technologies (PBF) and Directed Energy Deposition (DED) based technologies. Both of these technologies can be further classified based on the type of energy source used. In PBF based technologies, thermal energy selectively fuses regions of powder bed. Selective laser sintering/melting (SLS/SLM) and electron beam melting (EBM) are main representative processes of PBF based technologies. In DED based technologies focused thermal energy is used to fuse materials (powder or wire form) by melting as they are being deposited. Laser Engineered Net Shaping (LENS)/Direct Metal Deposition (DMD), Electron Beam Free Form Fabrication (EBFFF) and arc based AM are some of the popular DED based technologies. Most of above mentioned SFF/AM methods are capable to produce functionally gradient materials (FGMs) from thick coatings to complicated FGM bulk parts.

Advantages offered by AM techniques like higher material utilization, speed of production, design freedom, capability to produce complicated parts and less energy intensiveness are garnering particular interest in manufacturing FGMs for different applications.

Powder bed fusion (PBF) based AM technologies like Selective laser melting (SLM) and Electron beam melting (EBM) are very popular methods for producing complicated parts owing to their high accuracy and surface finish as compared to directed energy deposition (DED) based technologies. However, PBF based technologies are less flexible than DED based technologies as far as functionally gradient material manufacturing are concerned. It is due to fact that material gradient by varying chemical composition of powder is not possible. However these methods can produce bulk FGMs by controlling porosity or by introducing different types of lattice structures in parts to be manufactured.

Directed energy deposition (DED) based AM techniques are most convenient methods to produce FGMs since these methods can produce FGM from thick coatings to bulk parts having continuous or discontinuous gradient. These methods can produce FGMs with better adhesion and mechanical properties than powder bed technologies. Laser metal deposition (LMD) and Electron beam free form deposition (EBFFF)/ Electron beam additive manufacturing (EBAM) are popular methods based on DED based AM systems which can be used to manufacture different kinds of FGMs.

2.4.1. Laser metal deposition (LMD):

Laser engineered net shaping (LENS) and direct metal deposition (DMD) are main processes based on DED technology which uses laser beam as power source and raw material in the form of powder. LENS process was originally developed by Sandia national laboratories in 1997 and then licensed to Optomec (USA), whereas DMD process was jointly developed by POM group and University of Michigan [8, 9]. In these process, high power laser beam is used to create a molten pool on base material and then powder material is injected into the molten pool by using nozzles.

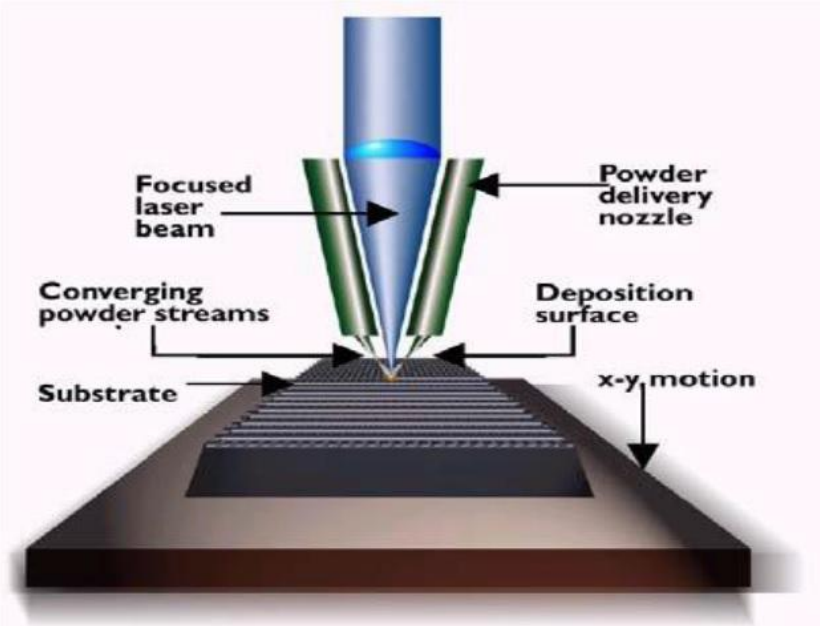

Figure 1. BasicLaser Engineered Net Shaping Process [10]

Delivered powder at laser beam spot is absorbed into the melt pool and creates deposit. As shown in figure 1, the work table can move in x - y direction to obtain desired cross section of sliced model and then subsequent layers can be deposited by incrementing deposition head in z direction to complete the object. Deposition of layers is repeated until the desired three dimensional componentshave been additively formed. Metal powder is delivered through nozzles and distributed around the circumference of deposition head either by gravity, or by using inert carrier gas.
The entire process is conducted under controlled argon atmosphere where oxygen levels are maintained below 10 ppm.

2.4.2. Electron beam direct manufacturing:

Electron Beam Direct Deposition (EBDM) is another technology based on directed energy deposition (DED) which uses electron beam as power source and raw material in the form of wire. This technology was developed by Sciaky (Chicago, USA) and also known as Electron beam additive manufacturing (EBAM). This process can produce medium to large sized near net shaped components inside vacuum chamber directly from digital model. After manufacturing, component requires finishing operations such as heat treatment and machining. Maximum size of component to be manufactured by EBAM is restricted by vacuums chamber size of the machine. Commercially available welding wires are used as the deposition material. The standard electron beam system is a Sciaky 60 kW / 60 kV welders. The electron beam is electronically focusable and the output power is scalable over a very wide range. This enables a very wide range of deposition rates to be achieved using the same system. Typical deposition rates of EBAM systems are from 3 to 9 Kgs/hrs depending on the material used and part complexity. Additionally, the EBAM system has closed loop control system in which melt pool size is continuously monitored and parameters are adjusted to keep the size constant. This ensures consistent part geometry, uniform microstructure and mechanical properties.

Figure 2. Electron Beam Additive Manufacturing by Twin Wire Deposition [12]

2.4.3. FGMs by Arc deposition technologies:

Wide ranges of arc based additive manufacturing processes are available where arc (plasma, TIG, MIG) is used as power source and material is used in the form of powder or wire. Plasma transferred arc (PTA) and plasma arc welding (PAW) are free form AM processes which uses plasma arc as power source and raw material in the form of powder and wire respectively. Shaped metal deposition (SMD) is another AM technique which uses tungsten inert gas (TIG) or Metal inert gas (MIG) welding with material in the form of wires for free form fabrications. Since most of such systems are wire feed type, these are also known as Wire assisted additive manufacturing (WAAM) systems. Large number of system configurations can be achieved by integrating conventional welding systems with robots, manipulators or gantries for automation. Allof these processes with proper inert gas shielding have strong potential to produce near net shaped medium to large sized parts at much lower cost as compared to laser and electron beam based processes.

References

[1] Shahistha A, Varghese B, Baby A 2014 A review on functionally graded materials TheInternational Journal Of Engineering And Science (IJES), Volume **3**,Issue 6, Pages 90-101,ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805.

[2] Mahamood R, Akinlabi E, Shukla M and Pityana S 2012 Functionally graded materials: Anoverview Proceedings of the World Congress on Engineering 2012 Vol.**3**, WCE, London, U.K.

[3] J. F. Groves, and H. N. G. Wadley 1997 Functionally graded materials synthesis via low vacuum directedvapor deposition Composites Parts B **28**B, (1997), 57-69.

[4] R. Knoppers, J. W. Gunnink, J. Van den Hout, and W. Van Vliet The reality of functionallygraded material products TNO ScienceandIndustry, The Netherlands, pp 38-43.

[5] Zhu J, Lai Z, Yin Z, Jeon J, and Lee S Fabrication of ZrO2–NiCr functionally graded materialby powder metallurgy Materials Chem. Phys. 68 130. Crossref.

[6] Watanabe Y, Inaguma Y, Sato H, and Miura-Fujiwara E 2009 Novel fabrication method forfunctionally graded materials under centrifugal force: the centrifugal mixed-Powder methodMaterials, Vol. **2**, No. 4, pp.2510-2525.

[7] Bhavar V, Kattire P, Patil V, Khot S, Gujar K, Singh R 2014 A Review on Powder bed fusion technology of metal additive manufacturing AMSI Conference 2014, Banglore, India.

[8] Ruan J, Sparks T, Fan Z, Stroble J, Panackal A and Liou F 2006 A Review of Layer Based Manufacturing Processes for Metals Solid freeform fabrication symposium, January 2006.

[9] Thymianidis M, Achillas C, Tzetzis D, Iakovou E, Pariente F, Guagliano M. 2012 ModernAdditive Manufacturing Technologies: An Upto-Date Synthesis and Impact on Supply ChainDesign", 2nd International conference on supply chains, October -2012.
[10] Hedges M., Calder N 2006 Near Net Shape Rapid Manufacture & Repair by LENS Cost Effective Manufacture via Net-Shape Processing, pp. 13-1 – 13-14. Meeting Proceedings RTOMP- AVT-139, Paper 13. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.
[11] Rasheedat M. Mahamood, Esther T. Akinlabi, Mukul Shukla and SisaPityana, 2012. Functionally Graded Material: An Overview. Proceedings of the World Congress on Engineering, Vol III.
[12] Zahra Sharif Khodaei, 2005. Preliminaries to Modeling and Analysis of Functionally Graded Materials. Czech Technical University in Prague.
[13] J.D. Claytona, J.J. Rencisb, 2000. Numerical integration in the axisymmetric finite element formulation. Advances in Engineering Software, 31: 137–141.
[14] Ahmet N. Eraslan, 2003. Elastic–plastic deformations of rotating variable thickness annular disks with free, pressurized and radially constrained boundary conditions. IJMS, 45: 643–667.
[15] Ashraf M. Zenkour, Daoud S. Mashat, 2011. Stress Function of a Rotating Variable-Thickness Annular Disk Using Exact and Numerical Methods. SCIRP Engineering, 3: 422-430.
[16] J.N.Sharma, Dinkar Sharma, Sheo Kumar 2011. Analysis of Stresses and Strains in a Rotating Homogeneous Thermoelastic Circular Disk by using Finite Element Method. International Journal of Computer Applications, Volume 35– No.13 (0975 – 8887).
[17] HasanCallioglu, 2011. Stress analysis in a functionally graded disc under mechanical loads and a steady state temperature distribution. Sadhana Vol. 36, Part 1: 53–64.
[18] Maruthi B H, M. Venkatarama Reddy, K. Channakeshavalu, 2012. Finite Element Formulation for Prediction of Over-speed and burst-margin limits in Aero-engine disc. International Journal of Soft Computing and Engineering (IJSCE), Volume-2, Issue-3.
[19] M. Shariyat, R.Mohammadjani, 2013. Three-dimensional compatible finite element stress analysis of spinning two-directional FGM annular plates and disks with load and elastic foundation non uniformities. LAJSS, 10: 859 – 890.
[20] Mohammad ZamaniNejad, Mehdi Jabbari, Mehdi Ghannad, 2015. Elastic analysis of FGM rotating thick truncated conical shells with axially-varying properties under non-uniform pressure loading. Composite Structures, 122: 561–569.
[21] J N. Sharma, Dinkar Sharma, Sheo Kumar, 2012. Stress and strain analysis of rotating FGM Thermo elastic circular disk by using FEM. International Journal of Pure and Applied Mathematics, Volume 74 No. 3: 339-352.
[22] AbdurRosyid, MahirEs-Saheb, Faycal Ben Yahia, 2014. Stress Analysis of Nonhomogeneous Rotating Disc with Arbitrarily Variable Thickness Using Finite Element Method. Research Journal of Applied Sciences, Engineering and Technology, 7(15): 3114-3125.
[23] Nguyen DinhDuc, Vu ThiThuyAnh, Pham Hong Cong, 2014. Nonlinear axisymmetric response of FGM shallow spherical shells on elastic foundations under uniform external pressure and temperature. European Journal of Mechanics A/Solids, 45: 80-89.
[24] Minwoo Hong, Ilwook Park, Usik Lee, 2014. Dynamics and waves characteristics of the FGM axial bars by using spectral element method. Composite Structures, 107: 585–593.
[25] Manish Bhandari, Dr.KamleshPurohit, 2014. Analysis of Functionally Graded Material Plate under Transverse Load for Various Boundary Conditions. IOSR-Journal of Mechanical and Civil Engineering, Volume 10, Issue 5: 46-55.HassanZafarmand, MehranKadkhodayan, 2015. Nonlinear analysis of functionally graded nanocomposite rotating thick disks with variable thickness reinforced with carbon nanotubes. Aerospace Science and Technology, 41: 47–54.