REVIEW OF FUNCTIONALLY GRADED MATERIALS

Received: 05 October 2015 / Accepted: 20 November 2015

Abstract: The present work reviewed about Functionally Graded Materials (FGMs) as the functionally graded materials (FGMs), an innovative material belongs to a class of advanced material with varying properties over changing dimension. The final properties of FGM are unique and different from any of the individual material that forms it. Typically, under harsh temperature conditions, the conventional materials (metals or ceramics) alone may not survive which led to development of a advance material i.e Functionally graded material which is capable of withstanding high temperature under harsh conditions. Functionally graded materials are widely used in aircrafts, space vehicles and other products working at elevated temperatures. The area of application of FGMs is expected to increase as the cost of material processing and fabrication processes are reduced by improving these processes.

Key words: Functionally graded materials, advanced materials, applications of FGMs

1. INTRODUCTION

The term material refers to a substance out of which something can be fabricated. The term 'materials' broadly describes everything we use to manufacture everyday objects from toys to automobile parts. But under the effect of high temperature and/or thermal gradients, the conventional materials (metals or ceramics) alone may not survive; we need advanced materials that provide high specific performance in comparison with conventional materials. Advanced materials are used for products that have some better properties. [1]

Functionally graded material (FGM) is relatively a new concept and is used for components/parts subjected to high thermo-mechanical loading. The technology for fabrication of FGM was first proposed in Japan in 1984 during a space plane project. Where a combination of materials used would serve the purpose of a thermal barrier capable of withstanding a surface temperature of 2000 K and a thermal gradient of 1000 K across a 10 mm section. Functionally Graded Material (FGM), an innovative material, belongs to a class of advanced materials with varying properties over changing dimension [2]. As shown in figure 1, traditional composites consist of two or more constituents that are combined at macroscopic level and are insoluble in each other in which the reinforcement material is uniformly distributed in the matrix material. Functionally graded materials are microscopically inhomogeneous composites usually made from a mixture of metal and a ceramic. One surface is generally a pure metal while the opposite surface is purely ceramic or a majority ceramic in which the metal surface provides the structural support while the ceramic surface provides thermal protection when subjected to high thermal gradient [3].

![Figure 1. Traditional Composites versus FGMs](image-url)

2. DISTRIBUTION OF REINFORCEMENTS

Several in order to study FGMs a model must be created that describes the function of composition throughout the material. The volume fraction, V, which describes the volume of reinforcement at any point, z, throughout the thickness, h, according to a parameter, n, which controls the shape of the function can be seen in Eqn. (1) below [4].

\[ V = \left( \frac{z}{h} + \frac{1}{2} \right)^n \]  

(1)
It follows that the volume fraction of matrix material in the FGM is $(1-V)$. A graphical representation of various values of the parameter $n$ can be seen in Fig. 2 below.

Figure 2. Variation in Parameter $n$.

The portion to the right of each line represents the amount of metal in the mixture and the portion to the left represents the ceramic component of the material. It should be noted that as $n$ approaches zero the material approaches a homogeneous ceramic, while as $n$ approaches infinity the material becomes entirely metal. At any point in between zero and infinity the material will contain both metal and ceramic. When $n$ is set equal to one, the distribution is linear containing equal portions of ceramic and metal. The property of a material through thickness varies as a function of the volume fraction and can be seen in Eqn. 2.

$$P(z) = (P_t - P_b)V + P_b$$  \hspace{1cm} (2)

Where $P_t$ and $P_b$ represent the material property of the top and bottom respectively. $P_t$ corresponds to $P_c$ or the material property of the pure ceramic and $P_b$ corresponds to $P_m$ or the material property of the pure metal. This equation holds true for the many material properties like modulus of elasticity, density, thermal expansion, thermal conductivity and Poisson’s ratio.

3. VARIOUS PROCESSING TECHNIQUES FOR FUNCTIONALLY GRADED MATERIALS

3.1. Vapour Deposition Technique: The various techniques of vapour deposition includes: (I) Chemical Vapour Deposition (CVD), (II) Sputter deposition and (III) Physical Vapour Deposition (PVD). These methods are energy intensive and a poisonous gas is produced as a byproduct. An excellent microstructure can be produced by using vapour deposition methods but only thin surface coating can be produced. [5]. The advantage includes that very thin layers can be produced and graded structure is easy to control by simply varying the composition of the gas phase. On the other hand attention must be paid on heat treatment process to avoid interdiffusion between the substrate and graded film.

3.2. Powder metallurgy: In order to produce functionally graded materials through Powder metallurgy the following three steps are involved. In first step, material A and material B are weighed, as shown in Fig. 3 (a), and then the two materials are mixed homogeneously by a V-shape mill, as shown in Fig.3(b). After that, stepwise staking of premixed powder can be obtained by predesigned spatial distribution of the composition Fig. 3(c). Finally spark plasma sintering (SPS) as shown in fig. 3(d) which is one of the most advanced method makes possible sintering high quality materials in small periods by charging the intervals between powder particles with electrical energy and high sintering pressure. The functionally graded material produced is a stepwise structure, and it is difficult to manufacture the functionally graded materials with continuous gradients. [6]

3.3. Centrifugal casting: Centrifugal casting is a pressure casting in which the gravitational force is increased by spinning the mould as shown in figure 4.

Figure 3. Fabrication process of the FGMs by powder metallurgy method. [6]

Figure 4. Apparatus for the centrifugal method. [6]

In centrifugal casting process the plug is pulled out to pour the molten metal from the inlet directly into the spinning mould. Before casting the spinning mould is preheated and the magnitude of the centrifugal force is expressed in G number, and G number is the ratio of the centrifugal force to the gravity, $g$, as given by the following equation:

$$G = \frac{2DN^2}{g}$$  \hspace{1cm} (3)

where $D$ is the diameter of the cast ring (m) and $N$ is the rotation speed of the mould (s-1). Lastly the furnace
is removed and the mould is cooled until complete solidification of the mould takes place. [6]

3.4. Centrifugal Slurry Method: Although the powder metallurgy has many advantages to fabricate the FGMs, yet it is difficult to manufacture the FGMs with continuous gradients. By combination of the powder metallurgy and a centrifugal slurry method, this shortcoming can be overcome. In this method, two types of solid particles will be used in the slurry, one is high-velocity particle with larger density and/or larger particle size and the other one will be low-velocity particle with smaller density and/or smaller particle size. The particles gradients can be controlled by the difference of migration rate between the two kinds of particles. After complete sedimentation occurs, the left behind liquid part of the slurry will be removed, and a green-body with continuous gradient can be obtained. The green-body is, then, sintered by SPS or other sintering methods, and finally an FGM with continuous gradient can be produced. [6]

Figure 5. Schematic illustrations of the centrifugal slurry-pouring method. [6]

3.5. Centrifugal mixed-powder method: Figure given below shows centrifugal mixed-powder method for production of FGMs under the centrifugal force.

Figure 6. The schematic description of the centrifugal mixed-powder method. [7]

To begin with, take a mixture of metal matrix particles A and dispersion particles B and insert them into a spinning mould, as shown in figure 6 (a). In the next step, molten metal matrix A is poured into the spinning mould with powder mixture A + B, as shown in Fig. 6 (b). Because of centrifugal force molten metal, A, penetrates into the space between the particles, as shown in Fig. 6 (c). At the same time, because of heat of molten metal matrix, the powder of matrix metal, A, is melted as shown in Fig. 6 (d). Finally, an FGM ring with dispersion-particles, B, spread on its surface, can be produced, as shown in Fig. 6 (e). [6]

4. APPLICATIONS OF FGMs

The concept of FGMs is applicable to many fields which are subjected to high thermo-mechanical loadings such as Aerospace, Chemical plants, Engineering, Electronics, Energy conversion, Biomaterial etc. There are several types of FGMs that exhibit exceptional multifunctional properties and multisectoral applications as shown below [8].

4.1. Thermal protection in diesel engines: Thermal Barrier Coatings (TBCs) are utilized in diesel engines for trucks, buses, locomotive, marine vehicles, tanks, military transport engines, and farm vehicles [9]. Their advantages in this application are increased power density, reduced heat loss, and reduced fuel consumption [10, 11]. In addition, TBCs have been shown to reduce exhaust emissions [12]. Figure 7 shows the commercial application of TBCs at various locations on a diesel engine. Thick (2.5 mm) TBCs are used on piston crowns, and thinner (0.5mm) ones are used on valve faces and cylinder heads. Experimental TBCs have been tested on cylinder liners, exhaust valve systems and valve seats [13]. It has been shown that a 5% reduction in fuel consumption is obtained by insulating the combustion chamber with 2mm thick functionally graded TBC. This performance gain could be increased to an overall 54% thermal efficiency for certain advanced diesel engine concepts. It has been shown that graded TBC have a much longer life time [14, 15, 16]

Figure 8. Location of TBCs on various components of Diesel Engine [17]

4.2. Medicine: Living tissues like teeth and bones are considered as functionally graded material from nature [18], and in order to replace these tissues, a suitable material is needed which will serve the purpose of the original bio-tissue. The ideal material for this
application is functionally graded material. FGM has find wide range of application in dental [19] and orthopedic applications for teeth and bone replacement.

4.3. Aerospace: Functionally graded materials has the ability of withstanding high temperature, which makes it suitable for use in aerospace industry but the processing cost of functionally graded material is high [20]. If processing technique is improved, FGM are promising and can be used in wider areas of aerospace.

4.4. Defense: One of the most important characteristics of functionally graded material is the ability to inhibit crack propagation. This property makes it useful in defense application, as a penetration resistant materials used for armour plates and bullet-proof vests [21].

5. CONCLUSION

Functionally graded material is an excellent advanced material that will revolutionize the manufacturing world in the 21st century. Functionally graded materials are very important in engineering and other applications but the cost of producing these materials makes it prohibitive in some applications. An overview is that this material can further be enhanced and also extended by bringing down the fabrication cost.

6. REFERENCES


Authors: Gagandeep Singh Kohli, Assistant Professor, Department of Mechanical Engineering, Baba Banda Singh Bahadur Engineering College, Fatehgarh Sahib, Punjab, India affiliated to Punjab Technical University, Kapurthala, Punjab, India.
Tejeet Singh, Associate Professor, Department of Mechanical Engineering, Shaheed Bhagat Singh State Technical Campus, Ferozepur, Punjab, India. 
E-mail: engg_kohli@yahoo.co.in

* (Corresponding Author)