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ISSN : 2278-0181

International Journal of Engineering Research & Technology

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Applications of Functionally Graded Materials (FGMs)

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Abstract:- In materials science functionally graded material (FGM) may be characterized by the variation in composition and structure gradually over volume, resulting in corresponding changes in the properties of the material. The materials can be designed for specific function and applications. Various approaches based on the bulk (particulate processing), perform processing, layer processing and melt processing are used to fabricate the functionally graded materials. There are many areas of application for FGM. The concept is to make a composite material by varying the microstructure from one material to another material with a specific gradient. This enables the material to have the best of both materials. If it is for thermal, or corrosive resistance or malleability and toughness both strengths of the material may be used to avoid corrosion, fatigue, fracture and stress corrosion cracking. The overall properties of FGM are unique and different from any of the individual material that forms it. There is a wide range of applications for FGM and it is expected to increase as the cost of material processing and fabrication processes are reduced by improving these processes. In this paper various applications of FGM have been discussed which might be very useful in the developments.

Keywords- CNT reinforced FGCMs, Applications, Functionally graded material, processing techniques, fabrication.

I. INTRODUCTION

The concept of FGM was first considered 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 temperature gradient of 1000 K across a 10 mm section. In recent years this concept has become more popular in Europe, particularly in Germany [3]. A transregional collaborative research center (SFB Transregio) is funded since 2006 in order to exploit the potential of grading monomaterials, such as steel, aluminum and polypropylene, by using thermo mechanically coupled manufacturing processes. Functionally graded materials in which some particular physical properties are changed with dimensions. Properties of such materials can be described by material function $f(x)$. In homogeneous materials this function is constant. Functionally graded materials (FGMs) refer to the composite materials where the compositions or the microstructures are locally varied so that a certain variation of the local material properties is achieved. Determination of compositional gradient and the process of making an FGM are dependent on its intended use. In this study, new possible applications of FGM and its production process were investigated [3-5]. FGMs are advanced composite materials that consist of two or more material ingredients that are engineered to have a continuous spatial variation of material properties. This is achieved by gradually changing the volume fractions and or microstructure of the constituent materials during fabrication. The constituent material phases for FGMs are chosen based on functional performance requirements. For example, metal/ceramic FGMs are used in high temperature applications. In a conventional thermal barrier coating, a layer of ceramic is bonded directly to a metallic structure. However, the abrupt transition in material properties across the interface between distinct materials can cause large interlaminar

stresses and may lead to plastic deformation or cracking. These adverse effects can be alleviated using FGMs by placing ceramic-rich material at the high temperature regions and metal-rich material at other regions where mechanical properties, such as toughness, need to be high with a gradual transition in between FGMs permit tailoring of material composition so as to derive maximum benefits from their in homogeneity and they offer great promise in applications where the operating conditions are severe, including spacecraft heat shields, coatings on gas turbine blades, plasma facings for fusion reactors, etc.

II. TYPES OF FGMs

Depending upon the nature of gradient, the functionally graded materials (composites) may be grouped into following types

- 1) Fraction gradient type (Fig. 1a)
- 2) Shape gradient type (Fig. 1b)
- 3) Orientation gradient type (Fig. 1c)
- 4) Size (of material) gradient type

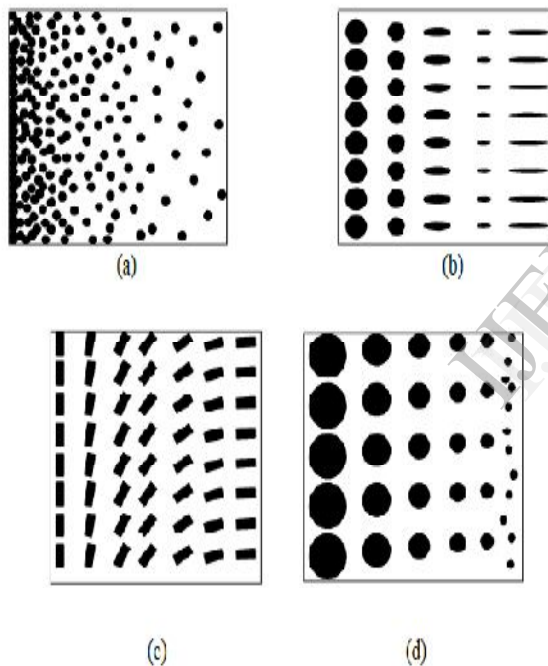


Fig. 1. Based on varieties of gradients, different types of functionally graded materials may be of (a) fraction gradient type, (b) shape gradient type, (c) orientation gradient type, and (d) size gradient type [1].

III. APPLICATION

Three application of FGM were proposed:-

1. ECAP (Equal-Channel Angular Pressing): - The novel technique in producing ultra fine grain of difficult-to-work materials by equal-channel angular pressing (ECAP) process at ambient temperature was developed by using FGM. The novel technique in producing ultra

fine grain of difficult-to-work materials by equal-channel angular pressing (ECAP) process at ambient temperature was developed by using FGM. For this study, Ti as the difficult-to-work material was tightly encapsulated in a hollow host material made of Al-based FGM matrix. The Al-based FGM as a host material assists the deformation of Ti. The ECAP process was simulated by the finite element method (FEM) to determine the appropriate compositional gradient of Al-based FGM and the position to embed Ti wire. FEM was conducted with Ti embedded into a different host material type as well as different die channel geometry. The strain distribution of the specimen after a single ECAP pass was analyzed. From the obtained results, it is found that the strain distribution in Ti is strongly influenced by the host material and the shape of the die channel. An experimental work was carried out to confirm the ability of the proposed technique in producing ultra fine grain of Ti. The host material was prepared by embedding Al-13Ti alloy into Al. Three types of the Al-13Ti alloys with different Al-13Ti volume fractions were used to prepare the host materials. ECAP for specimens was carried out for up to eight passes by route A. The microstructure and hardness of ECAP specimens were investigated. The changes in microstructure and the increase in the hardness value of Ti with increased number of ECAP passes are evidences showing that Ti is successfully deformed by this technique.

2. Crash Boxes:- New types of FGM crash boxes with stepwise strength gradient in longitudinal directions were proposed. The property of the proposed FGM crash boxes were analyzed using FEM. Crash behavior of the crash box under axial quasi-static and dynamic impact loads were studied. The obtained load-displacement curves and the crash failure patterns then were evaluated to assess the effect of the stepwise strength gradient of the crash-box. Moreover, four different shapes of cross-sectional i.e. square, circle, pentagon and hexagon were considered. The results show that the FGM crash box is superior to than the homogeneous crash box in overall crashworthiness. Although there were no trigger mechanism introduced, the FGM crash boxes experience the progressive crushing initiated at the impact side [7].

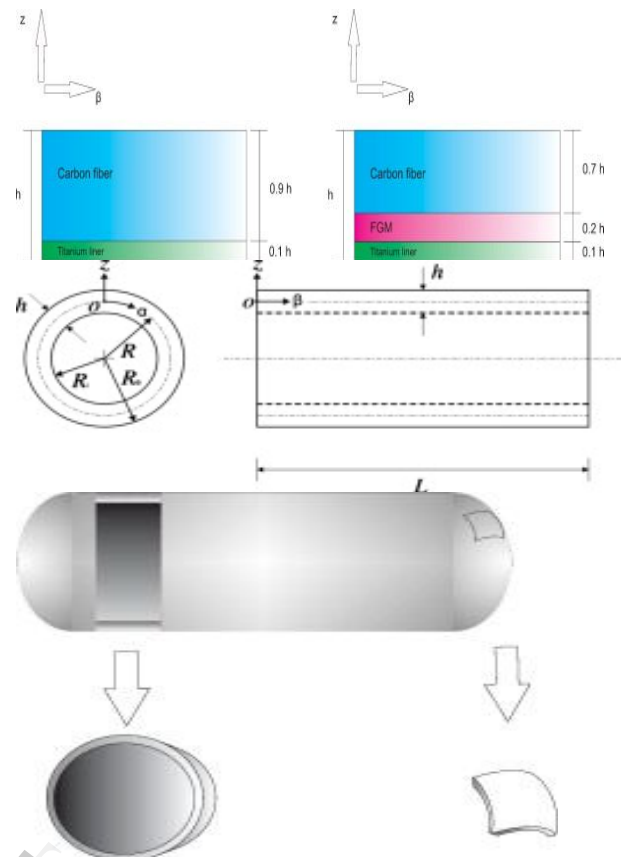
3. Thick Wall Pressure Vessel: - The FGMs were applied in pipe and pressure vessel field. A solution procedure for finite element thermo-viscoplasticity and creep analysis in an FGM thick-walled pressure vessel subjected to thermal and internal pressure was presented. The thick walled pressure vessel was replaced by a system of discrete rectangular cross-section ring elements interconnected along circumferential nodal circles. The property of FGM was assumed to be continuous function of volume fraction of material composition. The thermo-visco-plasticity and creep behavior of the structures were obtained by the use of an incremental approach. The obtained results show that the material composition significantly affects the stress as a

function of time at the inside and outside surface of thick-walled pressure vessel. The use of FGM can adjust the stress distribution in the structure. Moreover, one of the FGM fabrication method, centrifugal casting, was investigated [9].

Two types of centrifugal casting method namely, centrifugal solid-particle method (CSPM) and centrifugal mixed-powder method (CMPM), were used to fabricate Al/Sic FGM. Formations of graded distribution of Sic particles within molten Al by CSPM and CMPM under huge centrifugal force were examined and simulated. The movement of Sic particles in viscous liquid under centrifugal force was explained theoretically based on Stoke's law. The effect of composition gradient of particles on viscosity was taken into account. Also, the effect of temperature distribution on viscosity and density were considered. A computer code to simulate the formation of compositional gradient in an Al/Sic FGM manufactured by CSPM and CMPM was developed. From the obtained results, it was found that the Sic particles can be graded from inner to outer surface of Al/Sic FGM by CSPM. Meanwhile by CMPM, the Sic particles can be dispersed on the surface of Al/Sic FGM. The graded distribution in Al/Sic FGM under huge centrifugal force was significantly affected by the mold temperature but less affected by the initial temperature of molten Al and casting atmosphere [13-15].

IV. APPLICATIONS IN OUR NATION'S INDUSTRY

Improved tools and dies fabricated from functionally graded materials will be used in the aluminum, glass & steel industry. This work explores the possibilities of using functionally graded material (FGM) layers to reduce normal and shear stress gradients due to internal pressure and thermal loadings at the interface of a two-layered wall pressure vessel. The two walls are made of an internal thin metallic layer (titanium used as a liner to avoid a chemical/physical reaction between the gas and the external layer) and an external thick layer (carbon fiber used as a structural restraint). Two main geometrical elements are investigated: a cylindrical shell and a spherical panel. The shell analysis has been made by referring to mixed layer wise theories, which lead to a three-dimensional description of the stress/strain fields in the thickness shell direction; results related to the first order shear deformation theory are given for comparison purposes. It has been concluded that it is convenient to use FGM layers to reduce shear and normal stress gradients at the interfaces. Furthermore, the FGM layers lead to benefits as far as buckling load is concerned; lower values of in-plane shear and longitudinal compressive stresses are, in fact, obtained with respect to a pure two-layered wall [8].



A Functionally Graded Material (FGM) is a material which has a continuous variation of material properties through-the-thickness. This thesis will explore analysis of FGM flat plates and shell panels, and use FGM's unique characteristics to retrofit a cracked exhaust wash structure. FGMs are first characterized as flat plates under pressure and thermal loading. Next, FGM shell panels are characterized under thermal loading. Conclusions drawn from FGM characterization are used to develop a patch to retrofit a cracked aircraft exhaust wash structure. The exhaust wash structure is first analyzed to provide a baseline and then several FGM patches are evaluated on their ability to reduce stress and deflection. Finally, an exhaust wash panel made of FGM is analyzed [16].

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wash structure. The exhaust wash structure is first analyzed to provide a baseline and then several FGM patches are evaluated on their ability to reduce stress and deflection. Finally, an exhaust wash panel made of FGM is analyzed [17-18].

V. AREAS OF APPLICATION OF FGM

Some of the applications of functionally graded materials are highlighted below:

1. Aerospace: - Functionally graded materials can withstand very high thermal gradient, this makes it suitable for use in structures and space plane body, rocket engine component etc. If processing technique is improved, FGM are promising and can be used in wider areas of aerospace.

2. Medicine: - Living tissues like bones and teeth are characterized as functionally graded material from nature to replace these tissues, a compatible material is needed that will serve the purpose of the original bio-tissue. The ideal candidate for this application is functionally graded material. FGM has find wide range of application in dental and orthopedic applications for teeth and bone replacement.

3. 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 armor plates and bullet-proof vests.

4. Energy: - FGM are used in energy conversion devices. They also provide thermal barrier and are used as protective coating on turbine blades in gas turbine engine [18].

5. Optoelectronics: - FGM also finds its application in optoelectronics as graded refractive index materials and in audio-video discs magnetic storage media. Other areas of application are: cutting tool insert coating, automobile engine components, nuclear reactor components, turbine blade, heat exchanger Tribology sensors, fire retardant doors, etc]. The list is endless and more application is springing up as the processing technology, cost of production and properties of FMG improve [21-23].

VI. CURRENT AND FUTURISTIC APPLICATIONS OF FGM

Current and futuristic applications of FGM are listed as follows-

1. Commercial and Industrial:- Pressure vessels, Fuel tanks, Cutting tool inserts, Laptop cases, Wind turbine blades, Firefighting air bottles, MRI scanner cryogenic tubes, Eyeglass frames, Musical

instruments, Drilling motor shaft, X-ray tables, Helmets.

2. Automobiles :- (SiC-SiC) Combustion chambers , (AlSiC) Engine cylinder liners, (SiCw/Al-alloy) Diesel engine pistons, (E-glass/epoxy) Leaf springs, (Al-C) Drive shafts, (Al-SiC) Flywheels, Racing car brakes, (SiCp/Al-alloy) Shock absorbers.

3. Aerospace equipment and structures:- (TiAl-SiC fibers) Rocket nozzle, Heat exchange panels, Spacecraft truss structure, Reflectors, Solar panels.Camera housing, Turbine wheels (operating above 40,000 rpm), Nosecaps and leading edge of missiles and Space shuttle.

4. Sub-marine:- (Carbon and glass fibers) Propulsion shaft, (Graphite/Epoxy) Cylindrical pressure hull,(Glass/Epoxy) Sonar domes, Composite piping system, (Al-SiC) diving cylinders.

5. Biotechnology:- The functional gradient nano hydroxyapatite reinforced polyvinyl alcohol (nano HA/PVA) gel biocomposites can be prepared through a layer-by-layer casting method combining with freeze/thaw cycles technology. NanoHA/PVA gel biocomposites have been a promising and excellent artificial particular cartilage repair material. Compared to hydrogel-based materials such as poly(vinyl alcohol) (PVA), poly(lactic acid) and chitosan, nanoHA/PVA gel bio composites possesses superior bioactivity and mechanical properties because of the nano HA existence in the composites.

VI. FGM IN OPTOELECTRONIC DEVICES

Functionally graded materials (FGMs) are materials in which some particular physical properties are changed with dimensions. Properties of such materials can be described by material function $f(x)$. In homogenous materials this function is constant, like in Fig. 2a. In case of a junction of two different materials, function $f(x)$ has a stair-shape (Fig.2b).

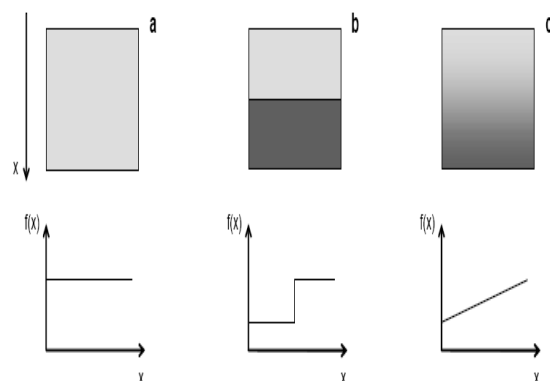


Fig. 2 Schematic representation of materials function in different structures; homogenous material (a), junction (b), FGM (c)

In FGM, this material function should be continuous or quasi-continuous. It means that the particular properties change continuously or quasi continuously along one direction, like it is shown in Fig. 2c. In many cases, FGM can be presented as a composition of several connected thin layers. Depending on the number of directions the properties changed, we can discriminate as 1- dimensional, 2- dimensional or 3- dimensional FGM [1-3]. It can be mathematically described for 3-D FGM as

$$\frac{dF}{dx} \neq 0, \quad \frac{dF}{dy} \neq 0, \quad \frac{dF}{dz} \neq 0$$

where $F(x, y, z)$ is the material function.

VII. APPLICATIONS OF FGM IN OPTOELECTRONICS

Now-a-days the graded materials are widely used for antireflective layers, fibers, GRIN lenses and other passive elements made from dielectrics, and also for sensors and energy applications. For example, the modulation of refractive index can be obtained in such components through the change in material composition. Another possibility is to apply concept of gradation in semiconductor active devices. In semiconductors the material function can describe energetic bandgap, refractive index, carrier concentration, carrier mobility, diffusion length, built-in electric field and another property which influence the parameters of optoelectronic devices.

VIII. APPLICATIONS OF CNT (CARBON NANO TUBES) IN FGM

CNT reinforced metal matrix functional graded composites due to their unique combination of hardness, toughness and strength are universally used in cutting tools, drills, machining of wear resistant materials, mining and geothermal drilling. CNT reinforced functional graded composite materials have the ability to generate new features and perform new functions that are more efficient than larger structures and machines. Due to functional variation of FGM-materials, their physical/chemical properties (e.g. stability, hardness, conductivity, reactivity, optical sensitivity, melting point, etc.) can be manipulated to improve the overall properties of conventional materials. Some of the current and futuristic applications of FGM are listed as follows.

VIII. OTHER APPLICATIONS OF CNT REINFORCED FGM

Potential applications of FGM are both diverse and numerous. Some more applications of CNT in FGM having recent applications are the following

- 1) CNT reinforced functionally graded piezoelectric actuators.
- 2) As furnace liners and thermal shielding elements in microelectronics.
- 3) CNT reinforced functionally graded tools and dies for better thermal management, better wear resistance, reduces scrap, and improved process productivity.
- 4) CNT reinforced functionally graded polyester calcium phosphate materials for bone replacement [24-25].

CONCLUSION

Functionally graded materials are very important in engineering and other applications but the cost of producing these materials makes it prohibitive in some applications. This study presents an overview on FGM, various fabrication methods were highlighted with solid freeform providing the best advantage over other processes because of the manufacturing flexibility it offers. An overview of different application areas is also presented and how the application area can further be enhanced and also extended by bringing down the fabrication cost through improving the most promising fabrication method. The novel technique in producing ultra fine grain of difficult-to-work materials by ECAP process at ambient temperature was developed by using FGM. The ECAP process was simulated by the FEM to determine the appropriate compositional gradient of Al-based FGM and the position to embed Ti wire.

ACKNOWLEDGEMENT

We wish to thank our network of colleagues and advisers. We also wish to thank our team that have been involved in various stages of this work. We thank JGI for providing this opportunity to us.

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