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A review on functionally graded materials

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ABSTRACT
In this paper a new and robust class of materials, widely referred to as Functionally Graded Materials (FGM) has been introduced. FGMs are entirely different from conventional alloys or composites in which the mechanical properties such as Young's modulus of elasticity, Poisson's ratio, shear modulus of elasticity, and material density, vary smoothly and continuously in preferred directions. These are a class of nature inspired materials. In this study, an overview of fabrication processes, areas of application, the various analytical approaches available in the literature for FGM modeling are presented and the vast application of this novel material has been illustrated using a case study in which behaviour of a latest material referred to as Functionally Graded Shape Memory Alloy composites (FG-SMA) has been analyzed. . Here, the work mainly concentrates on the transformation behaviour of FG-SMA composites subjected to thermal loading.

KEYWORDS—*Functionally Graded Materials, Processing Technique of FGM, Applications, Phase Transformation.*

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I. INTRODUCTION

In the development of our society materials have played an essential role. The scientific use of available base materials into various inorganic and organic compounds has made the path for developing the advanced polymers, engineering alloys, structural ceramics, etc. For satisfying the ever increasing requirements, newer and newer materials such as polymers, engineering alloys, structural ceramics and composites were developed. As the human race evolved from stone-age to the space age, the development of technology necessitated and was supported by the innovation of new materials.
The hierarchy of development of modern materials is illustrated in Fig. 1.1.

A. ALLOYS AND COMPOSITES

Pure metals were of little use in engineering applications because of the demand of conflicting property requirement. For example, an application may require a material that is hard as well as ductile, there is no such material existing in nature. To solve this problem, combination (in molten state) of one metal with other metals or non-metals is used. This combination of materials in the molten state is termed alloying (recently referred to as conventional alloying) that gives a property that is different from the parent materials. Bronze, alloy of copper and tin, was the first alloy that appears in human history. But there were limitations to the amount of material that can be dissolved. Also conventional alloying of two dissimilar materials with wide apart melting temperature was not possible.

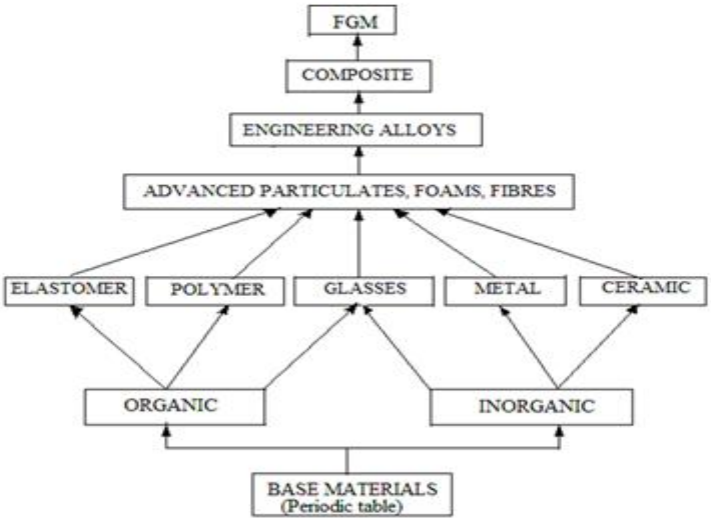

Fig 1.1 Representation of Modern Material Hierarchy

A method to overcome this was powdered metallurgy (PM) were alloys are produced in powdered form. In spite of its excellent characteristics, there existed some limitations which included intricate shapes and features that cannot be produced using PM, the parts were porous and had poor strength. With advancement composite materials were produced by combining one or more materials in solid states and had distinct physical and chemical properties different from the individual parent materials. These materials will fail under extreme working conditions through a process called de-lamination (separation of fibers from the matrix).

Functionally graded materials (FGMs) are the advanced materials in the family of engineering composites made of two or more constituent phases with continuous and smoothly varying composition. These advanced materials with engineered gradients of composition, structure and specific properties in the preferred direction are superior to homogeneous material composed of similar constituents. The mechanical properties such as Young's modulus of elasticity, Poisson's ratio, shear modulus of elasticity, and material density, vary smoothly and continuously in preferred directions in FGMs. FGMs have been developed by combining the advanced engineering materials in the form of particulates, fibers, whiskers, or platelets.

B. HISTORY OF FGM

Although the concept of FGMs, and our ability to fabricate them, appears to be an advanced engineering invention, the concept is not new. These sorts of materials have been occurring in nature. Bones have functional grading. Even our skin is also graded to provide certain toughness, tactile and elastic qualities as a function of skin depth and location on the body. The first FGM was developed in Japan in 1984 as the result of a space plane project. Later on many researches were done on this novel material. The FGM constituents engineered by humans commonly involve two isotropic material phases; although any numbers of chemically and spatially compatible configurations are possible. These components often include the engineering alloys of magnesium, aluminium, copper, titanium, tungsten, steel, etc. and the advanced structural ceramics such as zirconia, alumina, silicon-carbide, and tungsten-carbide.

In the continuous drive to improve structural performance, FGMs are being developed to tailor the material architecture at microscopic scales to optimize certain functional properties of structures. The concept of FGM is basically bio-inspired. Some naturally occurring FGMs and some human engineered ones are illustrated in Fig.1.2.

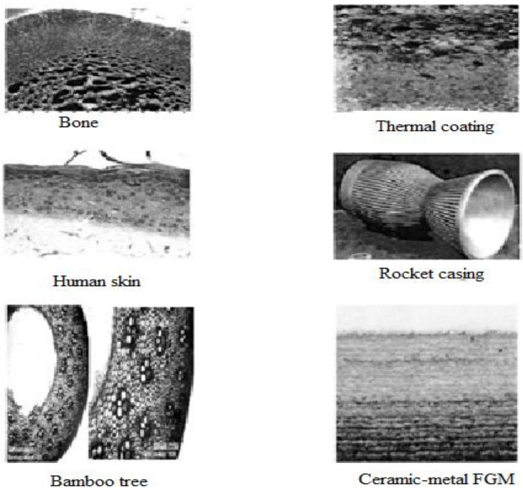

Fig 1.2 Some Examples of FGMs (Naturally occurring and Engineered by Humans)

C. ADVANTAGES OF USING FGM

These materials are gaining wide applications in various branches of engineering and technology with a view to make suitable use of potential properties of the available materials in the best possible way. This has been possible through research and development in the area of mechanics of FGMs for the present day modern technologies of special nuclear components, spacecraft structural members, and high temperature thermal barrier coatings, etc. These materials possess numerous advantages that make them appropriate in potential applications. It includes a potential reduction of in-plane and through-the thickness transverse stresses, improved thermal properties, high toughness, etc. FGMs consisting of metallic and ceramic components are well-known to enhance the properties of thermal-barrier systems, because cracking or de-lamination, which are often observed in conventional multi-layer systems are avoided due to the smooth transition between the properties of the components. The most common FGMs are metal/ceramic composites, where the ceramic part has good thermal resistance and metallic part has superior fracture toughness. A continuously graded microstructure with metal/ceramic constituents is represented in Fig.1.3 schematically for illustration.

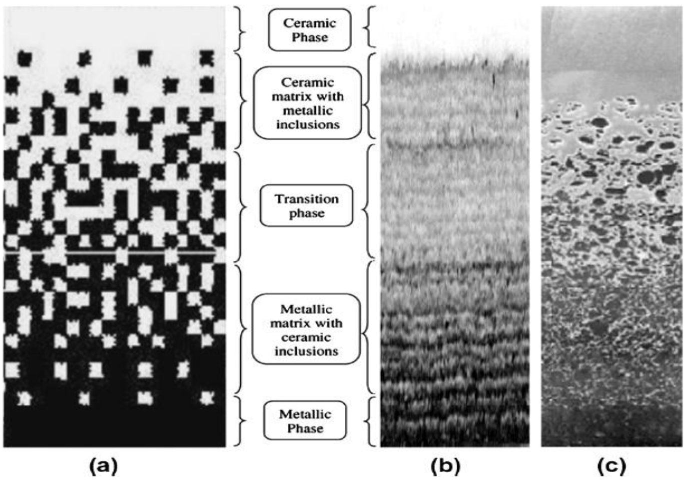

Fig 1.3 Schematic of Continuously Graded Microstructure with Metal-Ceramic Constituents (a) Smoothly Graded Microstructure (b) Enlarged View and (c) Ceramic–Metal FGM.

II. FABRICATION PROCESS

There are different kinds of fabrication processes for producing functionally graded materials. Functionally graded materials can be divided into two broad groups namely: thin and bulk FGM. Thin FGM are relatively thin sections or thin surface coating, while the bulk FGM are volume of materials which require more labour intensive processes. Thin section or surface coatings FGM are produced by Physical or Chemical Vapors Deposition (PVD/CVD), Plasma Spraying, Self-propagating High temperature Synthesis (SHS) etc. Bulk FGM is produced using powder metallurgy technique, centrifugal casting method, solid freeform technology etc.

A. THIN FUNCTIONALLY GRADED MATERIALS
Thin functionally graded materials are usually in the form of surface coatings, there are a wide range of surface deposition processes to choose from depending on the service requirement from the process.

a) Vapour Deposition Technique
There are different types of vapour deposition techniques, they include: sputter deposition, Chemical Vapour Deposition (CVD) and Physical Vapour Deposition (PVD). These vapour deposition methods are used to deposit functionally graded surface coatings and they give excellent microstructure, but they can only be used for depositing thin surface coating. They are energy intensive and produce poisonous gases as their byproducts.
Other methods used in producing functionally graded coating include: plasma spraying, electrodeposition, electrophoretic, Ion Beam Assisted Deposition (IBAD), Self-Propagating High-temperature Synthesis (SHS), etc.

B. BULK FUNCTIONALLY GRADED MATERIALS
The above mentioned processes cannot be used to produce bulk FGM because they are generally slow and energy intensive, therefore they are uneconomical to be used in producing bulk FGM. Some of the fabrication methods for producing bulk functionally graded materials are as follows:

a) Powder Metallurgy (PM)
Powder metallurgy (PM) technique is used to produce functionally graded material through three basic steps namely: weighing and mixing of powder according to the pre-designed spatial distribution as dictated by the functional requirement, stacking and ramming of the premixed-powders, and finally sintering. PM technique gives rise to a stepwise structure. If continuous structure is desired, then centrifugal method is used.

b) Centrifugal Method
Centrifugal method is similar to centrifugal casting where the force of gravity is used through spinning of the mould to form bulk functionally graded material. The graded material is produced in this way because of the difference in material densities and the spinning of the mould. Although continuous grading can be achieved using centrifugal method but only cylindrical shapes can be formed. Another problem of centrifugal method is that there is limit to which type of gradient can be produced because the gradient is formed through natural process (centrifugal force and density difference). To solve these problems, researchers are using alternative manufacturing method known as solid freeform.

c) Solid Freeform (SFF) Fabrication Method
Solid freeform is an additive manufacturing process that offers lots of advantages that include: higher speed of production, less energy intensive, maximum material utilization, ability to produce complex shapes and design freedom as parts are produced directly from CAD (e.g. AutoCAD) data.

SFF involves five basic steps:
- generation of CAD data from the software like AutoCAD, Solid edge etc.
- conversion of the CAD data to Standard Triangulation Language (STL) file
- slicing of the STL into two dimensional cross-section profiles
- building of the component layer by layer
- Removal and finishing.

There are various types of SFF technologies, laser based processes are mostly employed in fabrication of functionally graded materials. Laser based SFF process for FGM include: laser cladding based method, Selective Laser Sintering (SLS), 3-D Printing (3-DP), and Selective Laser Melting (SLM). Laser cladding based system and selective laser melting are capable of producing fully dense components. Solid freeform provide manufacturing flexibility amongst other advantages but the technology is characterized by poor surface finish making it necessary to carry out a secondary finishing operation. There are lots of research efforts in this direction to improve surface finish, dimensional accuracy etc.

III. APPLICATIONS OF FGM
FGMs have great potential in applications where the operating conditions are severe, including spacecraft heat shields, heat exchanger tubes, biomedical implants, flywheels, and plasma facings for fusion reactors, etc. Various combinations of the ordinarily incompatible functions can be implemented to create new materials for aerospace, chemical plants, nuclear energy reactors, etc. For example, a discrete layer of ceramic material is bonded to a metallic structure in a conventional thermal barrier coating for high temperature

applications. However, the abrupt transition in material properties across the interface between distinct materials can cause large inter-laminar stresses and lead to plastic deformation or cracking. These harmful effects can be eased by smooth spatial grading of the material constituents. In such cases, large concentrations of ceramic material are placed at corrosive, high temperature locations, while large concentrations of metal are placed at regions where mechanical properties need to be high. The application of these advanced materials was first visualized during a space plane project in 1984 in National Aerospace Laboratory of Japan to avoid the stress peaks at interfaces in coated panels for the space shuttle. Combination of materials used here served the purpose of a thermal barrier system capable of withstanding a surface temperature of 2000 K with a temperature gradient of1000 K across a 10 mm thick section. Later on, its applications have been expanded to also the components of chemical plants, solar energy generators, heat exchangers, nuclear reactors and high efficiency combustion systems. The concept of FGMs has been successfully applied in thermal barrier coatings where requirements are aimed to improve thermal, oxidation and corrosion resistance. FGMs can also find application in the communication and information techniques. Abrasive tools for metal and stone cutting are other important examples where gradation of surface layer has improved performance. Various major fields of application of FGM are:

A. 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.

B. 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 orthopaedic applications for teeth and bone replacement

C. DEFENCE

One of the most important characteristics of functionally graded material is the ability to inhibit crack propagation. This property makes it useful in defence application, as a penetration resistant materials used for armour plates and bullet-proof vests. FGMs have been known to increase the level of ballistics protection, up to 20 folds, at a reduced weight. This can be achieved because the FGMs are made up of an extremely hard surface layer (to absorb the energy of impact), a multilayered graded interface and a tough metal backing that accommodates deformation after ballistic impact.

D. 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. They are used in thermoelectric generators, sensors and solar cells.

E. 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 FGM improve.

IV. MATERIAL PROPERTIES

The accurate information of the shape and distribution of particles of FGM may not be available. Thus the effective material properties such as elastic modulii, shear modulii, density etc of the graded composites are being evaluated based only on the volume fraction distribution and the approximate shape of the dispersed phase. Several micromechanics models have been developed over the years to infer the effective properties of macroscopically homogeneous composite materials. The analytical approaches, both finite element methods and micromechanical models are frequently used for FGM modeling.The various analytical approaches available for FGM modeling are mentioned below:

A. SELF CONSISTENT ESTIMATES

This method assumes that each reinforcement inclusion is embedded in a continuum material whose effective properties are those of the composite. It does not distinguish between matrix and reinforcement phases and the same overall modulii are predicted in another composite in which the roles of the phases are interchanged. This makes it particularly suitable for determining the effective modulii in those regions which have an interconnected skeletal microstructure as shown in fig 4.1.

Fig 4.1 Two-phase material with skeletal microstructure

B. MORI-TANAKA SCHEME

This method works well for composites with regions of the microstructure having a clearly defined continuous matrix and a discontinuous particulate phase (Fig 4.2). The matrix phase is assumed to be reinforced by spherical particles of a particulate phase. Here K1, G1 and V1 represent the bulk modulus, the shear modulus and the volume fraction of the matrix phase whereas K2, G2 and V2 represent the bulk modulus, the shear modulus and the volume fraction of the particulate phase. It is noticed that $V1 + V2 = 1$.

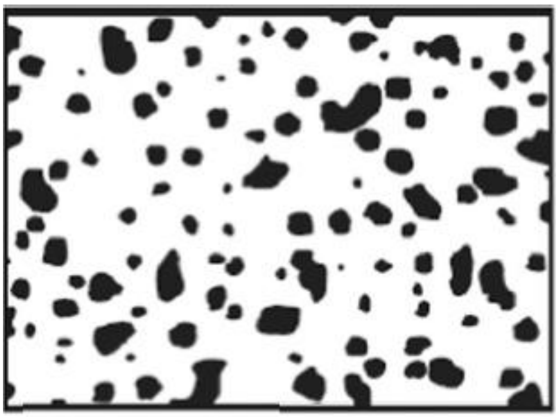

Fig 4.2 Two-phase material with particulate microstructure

C. COMPOSITE SPHERE ASSEMBLAGE MODEL

In this model the effective properties of isotropic composite materials have been determined analytically, which is based on the simplifying assumption that the composite material is filled with a fractal assemblage of spheres embedded in a concentric spherical matrix of different diameters such that the spheres completely fill the volume of the composite.

D. SIMPLIFIED STRENGTH OF MATERIALS METHOD

This method assumes that the matrix phase is reinforced with and ideally bonded to a periodic array of square fibres. It is a popular modelling method due to its ease of implementation and computational efficiency.

E. MICROMECHANICAL MODELS

This method attempts to accurately simulate the realistic microstructure of the RVE and determine the thermo-mechanical response due to applied loads such that the effective material properties may be calculated for various volume fractions of constituent reinforcement. In this manner various sets of data are collected for different material combinations. It is the most accurate method since the microstructure under consideration is directly modelled through 3-D finite elements.

V. RESEARCH RESEARCHES AND FG-SMA

Lots of studies have been conducted on behavior of functionally graded materials and the literature is very rich on this because of the wide areas of application of this novel material. The concept of FGMs was proposed in 1984 by Japanese material scientists. Continuous changes in the composition, microstructure, porosity, etc. of these materials result in the gradients of properties such as mechanical strength, thermal conductivity and fracture toughness. Introduction to fundamentals of FGM was given by Suresh and Mortensen. After this many have attempted variety of analytical, numerical methods for studying the mechanical, thermal and dynamic response of structures made of FGMs.A comprehensive review on performance of FGM was published in 2007 by Birman and Byrd. A number of researches were also conducted in the areas of analysis and modeling work on FGM. Now, the vast application of FGM is illustrated by the behavior of a latest material referred to as Functionally Graded Shape Memory alloy composites (FG-SMA). Here the work mainly concentrates on the transformation behavior of functionally graded SMA composites subjected to thermal loading (Liu et al., 2013).

A. INTRODUCTION

Shape Memory Alloys (SMAs), which exhibit reversible martensitic transformation, have attracted great interests in various fields including aerospace, naval and biomedical due to interesting behaviours such as the shape memory effect, super elasticity and pseudo plasticity. As applications become more and more complex, there is an increasing demand for high-performance materials. To be well used in aerospace engineering, the SMA composites should meet the requirement of high temperature conditions and possess higher mechanical properties. The need for such advanced properties of SMA composites led researchers the idea of incorporating FGM with SMA to form a new class of advanced composites called Functionally Graded Shape Memory Alloy (FG-SMA) composites. It is known that an FGM composite consists of a metallic phase and ceramic phase. Here in FG-SMA composites, the metallic phase is constituted by SMAs, mostly the nitinol alloys which are the most widely used type of SMA. By developing such a composite, the transformation capabilities of the SMA can be combined with the tailoring offered through FGMs to produce a truly unique material such as for space vehicles subjected to high temperature environment. It introduces an artificial compressive residual stress and the mechanical properties of composites will be improved significantly. Furthermore, these composites have great potential to be used in new sensor technology, information technology and the emerging field of smart materials systems. Therefore, in order to optimally design the microstructure and properties of functionally graded SMAs, it is imperative to develop and implement an accurate model describing its overall properties.

Many studies had already been conducted on the properties, characterization and effective fabrication of FG-SMAs. It was found that compared to the homogeneous SMAs, the composite has different shape memory and pseudo-elastic behaviours. The corrosion resistance property was also found to get enhanced. Even though analytical solutions had been developed by researchers for FGMs and SMAs in the past history, no perfect analytical solution has been formulated for functionally graded SMAs. Since the properties of the composite are different from that of FGM or SMA, a different approach has to be adopted. This motivated the authors to present a theoretical model to study the phase transformation and describe the mechanical properties of functionally graded SMA materials. To obtain the effective properties of the composite, the averaging technique of composites for heterogeneous materials was utilized. A constitutive model that describes the thermo-mechanical behaviour of the SMA phase was adopted and then combined with averaging technique of composites so that the transformation of the composite is presented as well as assumptions of how the SMA model is used for the determination of the transformation strain in the SMA in homogeneities. The effective stresses of the SMA phase were calculated to judge the transformation of SMA phase. Finally, the analytical results of the constitutive model of the system were obtained.

B. ANALYTICAL SOLUTION OF FUNCTIONALLY GRADED SMAS

To analyze the transformation behaviour of functionally graded SMA composites, transformation characteristics of the composite under thermal loading were determined. From these considerations, the analytical expressions for the stresses in an active plate consisting of a three-layered system with a middle FG-layer were then derived according to the averaging technique of composites and a constitutive model of SMAs. Assume that the temperatures are all higher than the yield transformation temperature. The physical reason for such behaviours was explained, the average stress and the effective stress in each phase were then determined to get the behaviours of such composites.

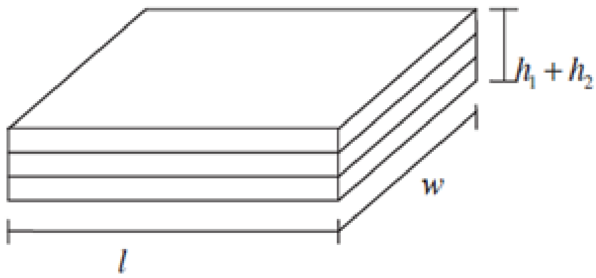

Fig 5.2.1 Analytical formulation of functionally graded SMAs

A three-layered system made up of a compositionally grade layer in between a homogeneous material and an SMA material was considered by Liu et al. As shown in Fig.5.1 the layer 1 is considered as the homogeneous ceramic and the up layer is considered as the SMA being the pure austenite at initial phase. The system is stress free at the initial case and the stress free is kept on all boundary surfaces. The total length, width and height of the multilayer system were designated by l, w and h1 + h2, respectively, as shown in Fig 5.1. It was assumed that l = w>>h1 + h2, which allows the model to be idealised by as an equal biaxial stress plate, and the variables of interest depend only on the out of plane coordinate z. The in-plane geometry of the layered structure is shown in Fig. 5.2. The FG-layer extends from z = -a to z = +a and for continuous property assumptions to be valid the thickness of this layer is considered to be significantly larger than its dominant micro-structural length scale. The interfaces between the different layers were assumed to be perfectly bonded at all times. The SMA phase is assumed to be initially at pure austenite phase and the multilayer system behaviour to be initially linear elastic.

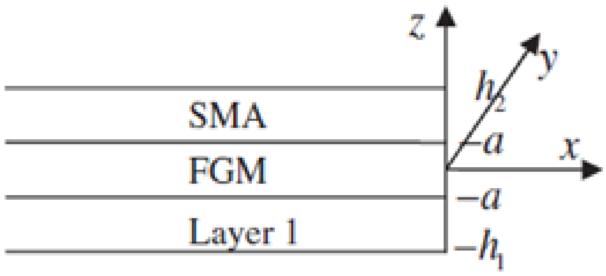

Fig 5.1 Three-Layered Structural Model

Fig 5.2 Coordinate Axes and Dimensions of the Three-Layered Plate System. The volume fractions of the SMA phase vary in the FG-layer as a function of ‘z’ coordinate, as described by the function V(z), which satisfies the following conditions at layer’s interfaces.

V(z)= 0, at z = -a
1, at z = a

The compositional gradation of the FG-layer is defined by the volume fraction of the SMA phase. Here, the following function of V(z) will be considered as:

$$V(z) = \left(\frac{z+a}{2a}\right)^m$$

where 'm' is a real number. This means that the gradation of the FG-layer is such that it changes from 100% of the ceramic phase at the bottom interface, to 100% of the SMA phase at the top interface. In the thermo-elastic phase it can be decomposed into an elastic component and a strain component. i.e.

$\varepsilon = \varepsilon^{e} + \varepsilon^{the}$

Under equal biaxial stress condition,

$\sigma_{xx}(z)=\sigma_{yy}(z)=\sigma(z)$;

$\varepsilon_{xx}(z)=\varepsilon_{yy}(z)=\varepsilon(z)$

Then the stress tensor and the strain tensor can be described as

$$\sigma_{ij} = \begin{pmatrix} \sigma(z) & 0 & 0 \\ 0 & \sigma(z) & 0 \\ 0 & 0 & 0 \end{pmatrix}; \qquad \varepsilon_{ij} = \begin{pmatrix} \varepsilon(z) & 0 & 0 \\ 0 & \varepsilon(z) & 0 \\ 0 & 0 & \dfrac{-2\varepsilon(z)}{1-\upsilon} \end{pmatrix}$$

According to the standard linear relation of Euler Bernoulli beam theory between the total in-plane strain and the laminate curvature (K), the thickness-wise variation of the in-plane strain can be expressed as follows

$$\varepsilon(z) = \varepsilon_o + Kz$$

where ε0 is the strain at the mid-plane of the FG-layer at z = 0.

The stress component σ(z) is given by

$$\sigma(z) = \frac{E(z)}{1-\upsilon}(\varepsilon_0 + Kz - \alpha(z)\Delta T)$$

where E(z) is the Young's modulus, α (z) is the coefficient of thermal expansion and υ is the Poisson's ratio respectively. Here ΔT = T – T0, where T0 is the initial temperature and T is the homogeneous temperature in the multilayer system.

Solving and deriving the equations for effective stress and strain, finally the relationship between the effective stress and strain could be obtained as

$$\sigma_e = \sqrt{\frac{3}{11}\frac{E(z)}{1+\upsilon}}\,\varepsilon_e$$

Where E(z) is the Young's modulus and υ is the Poisson's ratio for different layers respectively

According to averaging technique of composites, the system is analyzed by using different constitutive models in different phases and it leaves the thermo-elastic biaxial stress solution for an arbitrary FGM characterized by a generic composition profile function V(z).

And we can write σ(z) as,

$$\sigma(z)\begin{cases} \overline{E_1}(\varepsilon_0 + Kz - \alpha_1\Delta T), & -h_1 \le z \le -a \\ \overline{E_1}(\varepsilon_0 + Kz - \alpha_1\Delta T)[1 - V(z)] + V(z)\overline{E_2}(\varepsilon_0 + Kz - \alpha_2\Delta T), & -a \le z \le a \\ \overline{E_2}(\varepsilon_0 + Kz - \alpha_2\Delta T), & a \le z \le h_2 \end{cases}$$

Where $\bar{E}1 = E_1/1-\upsilon$ and $\bar{E}2 = E_2/1-\upsilon$.

For the solution of equations the force equilibrium and moment equilibrium conditions were applied. The stress distribution could be obtained by using the general expressions as shown above and several particular cases of gradation was treaded just by assigning the appropriate value to parameter m. The neutral axis position plays an important role in both the deformation analysis and stiffness calculation of the structures. Here there is a big effect of m on both the stress distribution and the neutral axis. In order to properly apply this work to structure deformation analysis and stiffness calculation, the variation of the position of the neutral axis with index m have to be analyzed. For any value of m, the neutral axis could be calculated using the following equation.

$Z = -(\varepsilon_o/K)$

B. Transformation analysis for functionally graded SMAs

To get the analytical solution of the functionally graded SMAs after transformation happens, stress distributions should be performed to demonstrate the phase transformation. As a starting point, the initial phase transition point should be determined first. To accomplish this task, the average stress of the three-layered system and the effective stress of the only SMA phase in both the FG-layer and the SMA layer were calculated, respectively. The material parameters in Table1are used to demonstrate the distributions of both stresses.

Table 5.1 Parameters used in Calculation for the Thermo-Elastic System

υ	E_1 GPa	$E_2=E_A$	a_1 ($^oC^{-1}$)	a_2 ($^oC^{-1}$)	$h_1=h_2=h$	T(^{o}C)	a
0.33	380	70	7.4x 10^{-6}	11.4x 10^{-6}	1	50	0.5

Fig 5.3 shows the distributions of the average stress and the effective stress through the FG-layer and SMA layer of the three-layered system with m = 1 at $\Delta T = 200\ ^oC$, respectively. The dotted curve represents the distribution of the average stress; the solid curve corresponds to the distributions of the effective stress for the SMA phase. As seen in Fig 8, all the effective stresses of FG-layer and SMA layer are linear tensile and higher than the average stresses. It is also observed that although the maximum average stress is in the FG-layer, the maximum value of the effective stress is in the SMA layer at h = 1. When the maximum value of the effective stress at h = 1 in the SMA layer equals to the yield stress of the SMA, the system starts transformation, then the system will not be elastic and the stress distribution will be changed. So the effective stresses of the only SMA phase in both the FG-layer and the SMA layer should be used to judge whether the system is transformed or not.

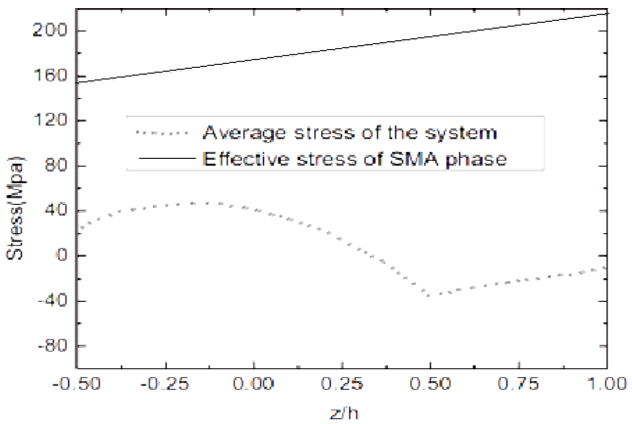

Fig 5.3 Compare the Effective Stress of SMA Phase to the System's Average Stress with

m = 1 at ΔT = 200 0C.

C. NUMERICAL RESULTS AND DISCUSSION

Effective stresses and strains are obtained for the transformed FG-SMA. It was noted that the stresses at the ceramic/FG-layer interface are always tensile whereas those at the metal/FG-layer interface are compressive in all cases. The stresses across the metal/FG-layer interface for different m and across the ceramic/FG-layer interface for different m are continuous. This is due to very gradual transition of the FGM composition near those interfaces. It can be easily found that there is no effect on the neutral axis by the temperature when the system is at elastic stage. It is just a function ofmand all the other parameters are given in Table.1. Then, the neutral axis for each value of m can be easily calculated. For values of m > 0 i.e., at m = 0.5,1 and 2,a stress distribution as shown in Fig 5.4 was obtained. But we can see that when we consider m=0, the model degenerates to a two-layered system and the stress distribution through the thickness of the two-layered system is obtained in Fig 5.5. As seen in Fig 5.5, the stresses of both the homogeneous austenite and ceramic layers are linear, and it is not continuous across the ceramic/SMA interface. So the three-layered system that is chosen is more reasonable than the two-layered one.

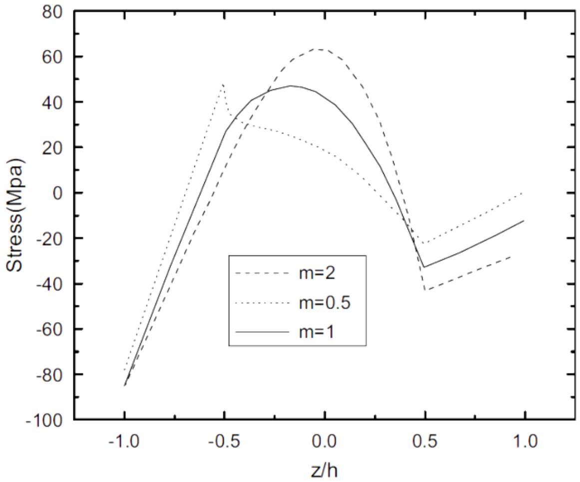

Fig 5.4 Stress Distribution for m=0.5,1,2 at ΔT=2000 C

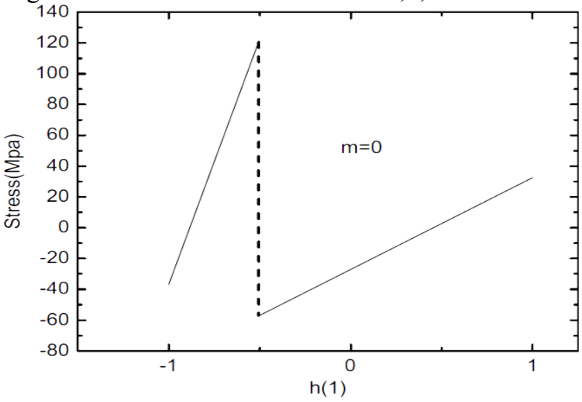

Fig 5.5 Stress Distribution at m=0 at ΔT=2000C

Fig 5.6 shows the stress distributions through the thickness of the three-layered system for m = 1 at ΔT = 265 0C. The dotted curve is the average stress distribution of the assuming pure elastic case with the same material parameters, while the solid curve is the average stress distribution of the functionally graded SMA. As seen in Fig 5.6, after the occurrence of phase transformation, the average stresses in both the SMA phase and ceramic phase are decreased. This shows that the transformation strain of SMA phase will decrease and the temperature resistant of the system will increase. So, the mechanical properties of SMA composites are enhanced than the normal FGMs, and can withstand higher temperature.

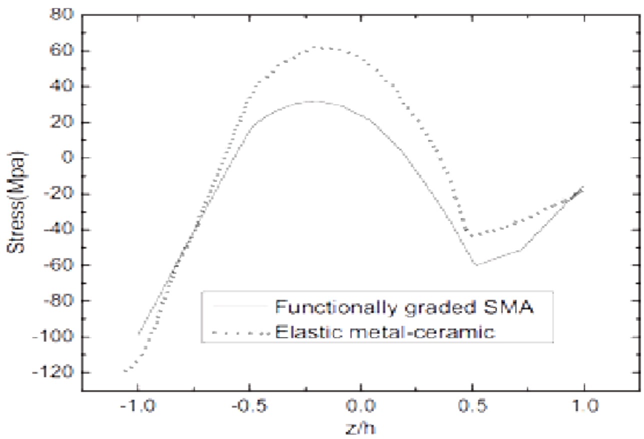

Fig 5.6 Compare the stress distribution of the functionally graded SMA to the pure elastic case of the system with m = 1 and ΔT = 265 0C.

VI. RESULTS

- Functionally graded materials are advanced materials having superior properties of heat resistance, suitability to be used at extreme temperature conditions and having suitable mechanical properties at the same time.
- Among various fabrication methods highlighted solid free form fabrication (SFF) technique gives better results because of the manufacturing flexibility it offers. More research needs to be conducted on improving SFF process so as to improve the overall performance and thus it will help in bring down the fabrication cost.
- FGMs can be incorporated with SMAs to produce robust materials called functionally graded SMAs that have advanced thermal and mechanical properties making them highly suitable in aerospace vehicles and other structures requiring improved temperature resistance and mechanical strength. Here the transformation behaviour of FG-SMA is studied and these studies could aid the researchers for the optimal design of such components and structures.
- FGM is the material of future which has possibilities for further level of studies and applications. Only lesser experimental studies are conducted in this field and there are only very few practical implementations so far, even though natural examples are many. The expensive nature of these materials also lays a hurdle to its development. It is expected that with further studies the acceptability and application of FGM may be further improved.

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