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Fabrication of Advanced Materials: A Review

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Abstract—*The growing demand for materials exhibiting multiple functionalities & having greater relevance to aerospace & other similar applications, have led researchers worldwide to focus more on developing such materials named Functionally Graded Materials(FGM), having properties that may be designed and controlled for desired functionality which include chemical, mechanical, thermal and electrical properties. Demand for Composite materials and structures are on the rise and widely accepted because of their better stiffness-to-weight ratio characteristic. However these materials have a drawback i.e. their failure at the interface between two adjacent layers known as delamination phenomena, which may lead to structural failure. This has been partially overcome with the development of FGM. Functionally Graded Material (FGM) belongs to a class of advanced materials with varying properties over a changing dimension. These advanced materials with engineered gradients of composition, structure and/or specific properties in the preferred direction/orientation are superior to homogeneous material composed of similar constituents. In this study, an overview of fabrication processes, some recent research studies and the need to focus more on research effort in improving the promising FGM fabrication methods such as Powder metallurgy (PM), Solid Freeform Solid Freeform Fabrication (SFF).*
Keywords*-Functionally graded material (FGM), Delamination, Powder Metallurgy, Solid free form Fabrication.*

I. Introduction

In the technical world FGMs were first proposed around 1984-85 when Japanese researchers studied advanced materials for aerospace applications working on a space plane project. The body of the space plane will be exposed to a very high temperature environment (about 1700°C), with a temperature gradient of approximately 1000°C, between inside and outside of the space plane. There was no uniform material able to endure such conditions. Therefore, the researchers devised a concept to fabricate a material by gradually changing (grading) the material composition (see Figure 4), and in this way improve both thermal resistance and mechanical properties. Most of the FGM applications are built as a coating on a surface build up by flame spray, CVD or spark plasma sintering. Therefore, all these applications have graded properties perpendicular to the surface but parallel to the surface the material composition is uniform. Pure metals are 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. To solve the problem of satisfying conflicting property requirements, combinations of metals with other metals or non metals are being established and are being worked upon. In case of metals, because of thermodynamic equilibrium limit, dissolution of one metal in another has certain limitations.

More over if the difference in the melting temperatures of the two alloying metals is quite large then combining them in traditional alloying process is also difficult. This problem is solved to some extent using the concept of powder metallurgy but the porous nature and poor strength characteristics have limited the use of powder metallurgy to nonstructural use. However, for structural applications, another option explored is manufacturing materials having conflicting properties by combining materials in the solid state which is referred as composite material. This composite material is a kind of advanced material, made of one or more materials combined in solid states with distinct physical and chemical properties [1]. They offer excellent combination of properties which the individual parent materials may or may not possess. Laminated composites are assemblies of layers of composites that are joined to provide some of the required engineering properties like the bending stiffness, in-plane stiffness, strength and coefficient of thermal expansion. The properties that may be designed and controlled for desired functionality include chemical, mechanical, thermal and electrical properties and the material properties are dependent on the spatial positions in the structure. These FGMs eliminate the sharp interfaces existing in laminated composite material thus avoiding the initiation of de-lamination failure by replacing the sharp interface with a gradient interface. Another important characteristic of FGM is the ability to tailor a material for specific application. Various characteristics of FGMs include elastic stress and strain, plastic yielding and deformation, and Creep at elevated temperature.

FGMs may be compositionally or micro-structurally graded. Depending upon the constituents, these FGMs are classified into several types, such as ceramic-metal, metal-metal and the like. Few new technologies have impacted product development as much as layer manufacturing techniques (LMT). Parts produced by LMT are based on adding material instead of removing, e.g. milling. The procedure is based on a 3D-CAD model, which is sliced into thin layers by arithmetical means, which can then be made individually as a stack of cross-sections resulting in the 3-dimensional part, e.g. the stereo lithography technique, see Figure 1.

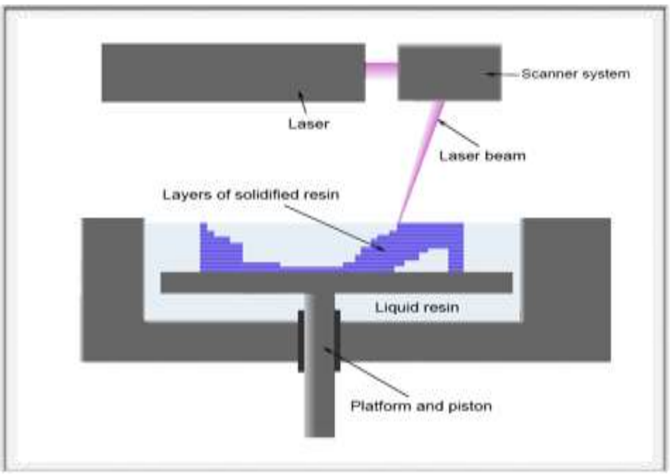

Fig1: Stereo lithography Process

There are many different techniques to make the slices. Each technique has its own advantages and limitations. In combination with 3D CAD it provides the product developer with a very powerful tool to optimize its design, and shortens the lead time for the product. New technologies such as concept modelers are able to produce prototypes with acceptable tolerances in a short time. The highest benefit in all layer manufacturing technologies comes from the reduced time to market. It is followed by fast changes in design and flexibility in technical changes both in design and manufacturing processes. Layer Manufacturing Technologies limit these changes to data and not hardware modifications. Hence, improvement of quality and product maturity resulting from testing and field experience can still be introduced without high cost of changing tools or manufacturing processes [1, 2]. LMT enables the possibility to create physical prototypes automatically without any human intervention during the realization of the part. Expanding the number of materials and improving the material properties used in these layer manufacturing processes gave the opportunity to create better quality prototypes.

Slowly the quality of the prototypes is improving and proved to have a functional quality. This is why nowadays, for small series, layer manufacturing technologies are used to produce actual end production parts. Production of end parts with a layer manufacturing technology is known as Rapid Manufacturing (RM).

Fig:2 Layered Manufacturing: Concept-Model-Slicing-3D Printing

II. Processing Techniques Of Functionally Graded Materials

Manufacturing Processes for the Functionally Graded Material are usually grouped as follows:
(a)Gradation Process: Building the spatially inhomogeneous structure
(b)Consolidation Process: Transforming this structure into a bulk material.

Gradation processes can again be classified as Constitutive process, Homogenizing process and Segregating process [4].Various Vapor Deposition Technique such as Sputter deposition, Chemical Vapor Deposition (CVD) & Physical Vapor Deposition (PVD) are used to deposit functionally graded surface coatings to obtain better microstructure, but the limitations are these techniques can only be used for depositing thin surface coating and are energy intensive and produce poisonous gases as their by-product. Other methods such as Plasma Spraying, Electro Deposition, Electrophoretic Deposition (EPD, Ion Beam Assisted Deposition (IBAD) and Self-Propagating High-temperature Synthesis (SHS) are also used to manufacture materials with functionally graded coatings [5, 6].

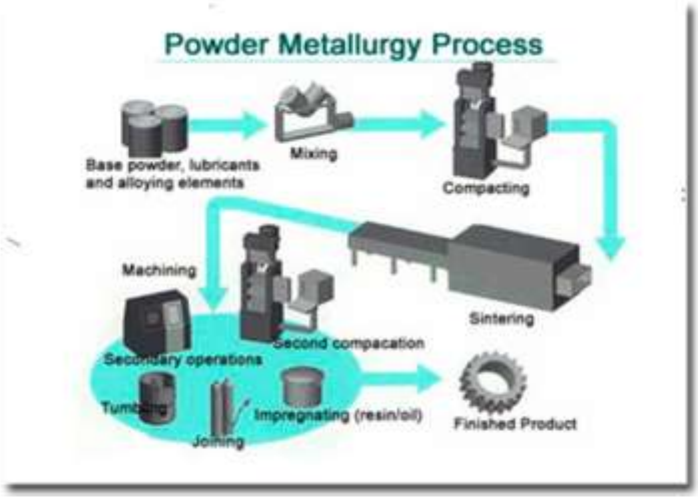

Fig:3 Powder Metallurgy Process

2.1 **Powder metallurgy (PM):** This technique is also used to produce functionally graded material through three basic steps. These include 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 sintering. This technique results a stepwise structure and when continuous structure is desired, the centrifugal method is used [7].

2.2 Centrifugal method: This centrifugal method is similar to centrifugal casting process, where the force of gravity is used through spinning of the mould to form bulk functionally graded material. One important advantage of this method is continuous grading can be achieved but the limitation is only cylindrical shapes can be formed. Also this method limits the type of gradient that can be produced and this issue can be solved by using alternative manufacturing method like the solid freeform.

2.3 Solid Freeform Fabrication (SFF): technique is an additive manufacturing process which offers lots of advantages that include 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, and lastly removal and finishing.

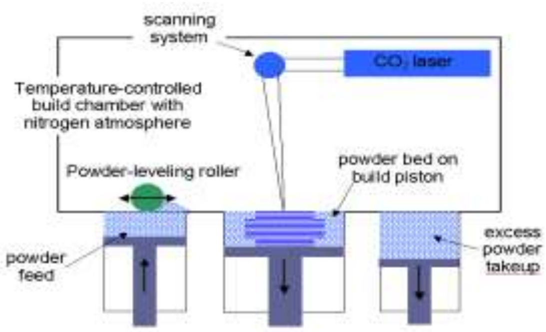

Fig. 4: Selective Laser Sintering process

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. [8] A comprehensive processing technique of functionally graded material is available in the literature, "Processing techniques for functionally graded materials", B. Kieback et al, [9].

III. Application Of Functionally Graded Materials

3.1 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. Because of high performance, temperature resistance capacity, FGMs are widely used as temperature shielding components in structures of aircraft, missile and nuclear plants. Conical shells and panels have a wide application in many aerospace vehicles which are increasingly made up of functionally graded materials. This necessitates more investigations on both static and dynamic behavior of FGM shell structures in general, and FGM conical shells and panels in particular. FGM will be more promising after the improvement of the processing technique. Ceramic-metal FGMs are particularly suited for thermal barriers in space vehicles. They have the added advantage that the metal side can be bolted onto the airframe rather than bonded as are the ceramic tiles used in the Orbiter. Other possible uses include combustion chamber insulation in ramjet or scramjet engines. FGMs have great potential in applications where the operating conditions are severe like the spacecraft heat shields and the heat exchanger tubes.

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3.2FG Materials in smart structures: The concept of a smart structure is described as a system which has intrinsic sensor, actuator and control mechanisms whereby it is capable of sensing a stimulus, responding to it, and reverting to its original state after the stimulus is removed. In other words, structures which are able to sense their environment self-diagnose their condition and adapt in such a way so as to make the design more useful and efficient. The analysis of a smart, functionally graded piezoelectric structure, shows that the smart structure consists of three layers: one layer of metal, one layer of piezoelectric material (PZT) used as an actuator, and a "graded metal/PZT" layer between the metal layer and the PZT layer. By introducing a functionally graded layer between the PZT actuator layer and the metal beam layer, both stress discontinuity and the edge local stresses can be essentially reduced. Liew et al. [10] analyzed the buckling and post buckling responses of FG cylindrical shells which are primary structural elements used in aircraft and aerospace structures.

3.3 Applications in Medicine: Living tissues like bones and teeth are characterized as functionally graded material from nature [12], 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 [13] and orthopedic applications for teeth and bone replacement [14]. 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 material used for armour plates and bullet-proof vests [15]. 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 [16, 17]. Optoelectronics: FGM also finds its application in optoelectronics as graded refractive index materials and in audio-video discs magnetic storage media.

IV. Recent Researches In FG Materials

A lot of studies have been conducted to understand the behavior of functionally graded materials, and there are many literatures available on the wide areas of application of these novel materials. A comprehensive review on performance of FGM was published in 2007 by Birman and Byrd, [11]. An overview on fracture behavior of FGM was conducted by Shanmugavel et al. A number of researches have also been conducted in the areas of analysis and modeling work on functionally graded material. There are still more to be done in terms of research to improve the performance of manufacturing processes of FGM.

4.1 The Future Scope of Research:

Functionally graded material is an excellent advanced material that will revolutionize the manufacturing world in the 21st century but there are a number of bottlenecks to realize this objective. Cost is a factor, with substantial part of the cost expended on powder processing and fabrication method. Solid freeform fabrication technique offers greater advantage for producing FGM, but there are still lots of issues that need to be resolved with this promising technology. More research needs to be conducted on improving the performance of SFF processes through extensive characterization of functionally graded material in order to generate a comprehensive database and to develop a predictive model for proper process control. More researches are very much essential for better process control through more powerful & improved feedback control for overall FGM fabrication process improvement (i.e. full automation). This will improve the overall performance of the process, bring down the cost of FGM and improve reliability of the fabrication process.

V. Conclusion:

Functionally graded materials find their applications in aerospace, automobile, medicine, sport, energy, sensors, optoelectronic etc. As the fabrication process is improved, cost of powder is reduced and the overall process cost is reduced, hence the application of FGM are growing every day. Owing to the importance of FGM, there are lots of research efforts at improving the material processing, fabrication processing and properties of the FGM.

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