International Journal of Engineering & Technology, 7 (4.39) (2018) 1-5

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

A Review of Solid State Processes in Manufacture of Functionally Graded Materials

Aravind Tripathy[1]*, Saroj Kumar Sarangi[2], Anil Kumar Chaubey[3]

[1]*Departmet of Mechanical Engineering, GIFT, Bhubaneswar*
[2] *Department of Mechanical Engineering, NIT, Patna*
[3]*Department of Advanced Materials Technology, CSIR-IMMT, Bhubaneswar*
**Corresponding author E-mail: aravindtripathy@yahoo.com*

Abstract

The demand for materials exhibiting multiple functionalities & having greater relevance to aerospace & other similar applications have led researchers to develop such materials named Functionally Graded Materials, having properties that may be tailored for a definite application. Better stiffness-to-weight ratio characteristic of such material is the main reason of their popularity today. Efforts are also directed to produce such materials in bulks and in a cost-effective manner. An overview of fabrication methods such as Powder metallurgy, Solid Freeform Fabrication, Laser cladding, Selective Laser Sintering, 3-D Printing and Selective Laser Melting etc. are deliberated here. The quality of FGM produced with better awareness, research and patronization at the state level is a continuous process, hence a review of solid state processes in manufacture of Functionally Graded Materials is the need of the hour.

Keywords: *Functionally graded material; Powder metallurgy; Solid Freeform Fabrication; Selective Laser Sintering; 3-D Printing.*

1. Introduction

It was around 1984-85, when the Japanese researchers, while working on their national aerospace project, Koizumi first talked of a special class of advanced material and coined the name Functionally Graded Material for the same [1]. To counter the steep temperature gradient of nearly a 1000°C that existed between outside to inside of the space craft, the Japanese researchers including Koizumi proposed to fabricate a material whose material property changed along a gradient and in the process improved the material property for playing multiple roles (heat resistance and structural characteristic). There is a decline in the use of pure metals for various engineering applications while at the same time there is a rise in popularity, hence a growing demand for materials with multiple functionality and conflicting property. For example, an application may require excellent structural property and at the same time it should be able to resist high temperature as well or an application that may require a material that is hard as well as ductile and there are no such readymade materials at our disposal in the nature. The solutions to such problems are to develop or fabricate a material which is a combination of a metal with another metals or non-metals. Satisfying conflicting property requirements, combinations of metals with other metals or non-metals are being established and are being worked upon to tackle the above-mentioned demand which is growing fast. The combination of different metals with other metals or non-metals and vice versa in varying compositions under different conditions, considering the material's inherent characteristics is not only complicated but also difficult as well as challenging on various accounts. Quality, reliability, repeatability is some of the most important challenges that prove to be the main hindrance to invent such materials and researchers find these challenges very intriguing. Creating such engineered materials is done primarily through two routes: one is the liquid state method i.e. by melting and casting and the while the other is through solid state methods such as Powder Metallurgy (PM) method [2,3].

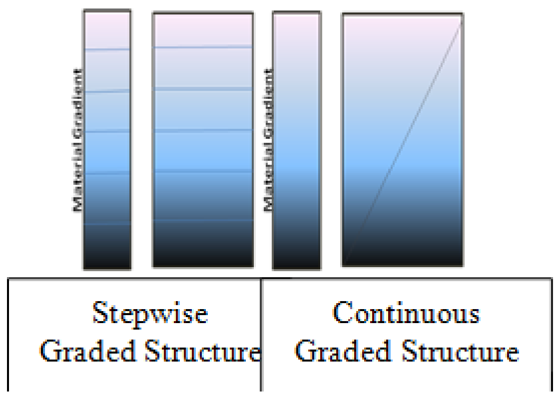

Fig.1: Schematic diagram of FGM

100% Al
90%Al+10%Al_2O_3
80%Al+20%Al_2O_3
70%Al+30%Al_2O_3
60%Al+40%Al_2O_3
50%Al+50%Al_2O_3

Fig.2: A typical functionally graded material prepared through PM route using Hot Press.

The concept of powder metallurgy is put to good use for creating such novel and engineered materials but the porous nature and poor strength characteristics have limited the use of powder metallurgy for non-structural use. For structural applications, another option explored is manufacturing materials having conflicting properties by blending materials in the solid state which is often referred to as composite materials. 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 [4]. They offer excellent combination of properties which the individual parent materials may or may not possess.

FGM properties which may be designed and fabricated for intended functionality include chemical, mechanical, thermal or electrical properties etc. and the material properties are dependent on the spatial position in the structure. One of the most important features of FGMs is the ability to tailor a material for an exclusive usage. Various characteristics of FGMs include elastic stress and strain, plastic yielding, 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 metal-ceramic, ceramic-metal, metal-metal and ceramic-ceramic etc. [5]. FGMs exhibit flexibility in terms of functional behavior of a single material as on one side it may exhibit metal like properties on the other side it will exhibit high temperature withstanding characteristics as that of a ceramic material. Scholars have applied the best methods or combinations of several methods depending on the characteristics of the constituent materials to successfully fabricate FGMs [3]. FGMs are prepared as shown in the figure below. The figure below depicts the FGM concept in a very clear manner. Today the researchers acknowledge the importance of innovative materials in use for economic and environmental reasons [6]. These engineered materials are designed for an intended function, and the material properties are tailored by a spatial gradation in structure and /or composition. FGMs exist in nature too. Like many other man-made materials, FGMs occurring in nature such as bamboo are in use for centuries for decoration and construction works [7].

2. Solid State Manufacturing Techniques for Functionally Graded Materials:

2.1. Powder Metallurgy:

PM process is one such most popular process in the field of FGM fabrication [8]. Here four basic steps are followed, namely: mixing, stacking, pressing and sintering as shown in the flow chart below. Mixing is Powder preparation, (precise weighing and blend the powder and ensure proper dispersion of each of them in the mixture which will significantly affect the structural properties), stacking is putting the powder in the die, pressing is applying the load through the punch to give shape to the material and in order to provide strength and integrity to the powder compact, controlled heating of the powder compact is facilitated and is known as sintering. Sintering temperature is usually below the melting point of the major constituent of the powder mix [2, 3] PM is an appropriate technology for both composite as well as FGM-fabrication and is widely being used too.

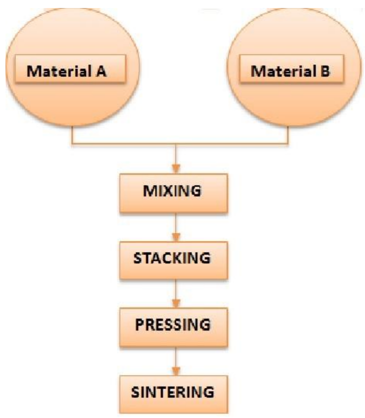

Fig. 3: Flow chart for Powder Metallurgy Process

In powder metallurgy (Fig.3), four basic steps are followed i.e. mixing, stacking, pressing and sintering as shown in the flow chart below. Mixing is Powder preparation, (precise weighing and blend the powder and ensure proper dispersion of each of them in the mixture which will significantly affect the structural properties), stacking is putting the powder in the die, pressing is applying the load through the punch to give shape to the material and in order to provide strength and integrity to the powder compact, controlled heating of the powder compact is facilitated and is known as sintering. Sintering temperature is usually below the melting point of the major constituent of the powder mix [6]. A sample metal-ceramic functionally graded material was fabricated using PM route pictorially described below (Fig.4). Uni-axial hot press was used to press and sinter the sample which were subsequently tested for various characteristics, some results are illustrated in fig.5 to fig.7 respectively. The samples showed good characteristics from mechanical and metallurgical perspectives.

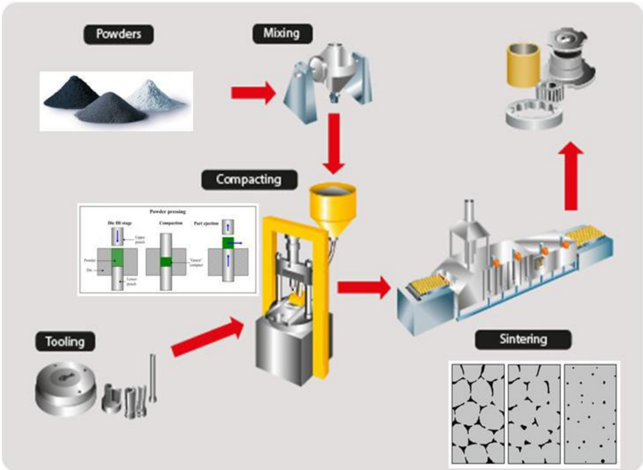

Fig. 4: Stages of Powder Metallurgy process

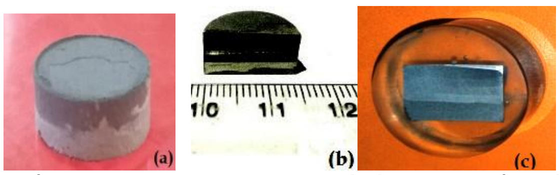

Fig.5: After compaction: (a) Raw FGM sample (b) Diameter of sample (c) Sample prepared for hardness test

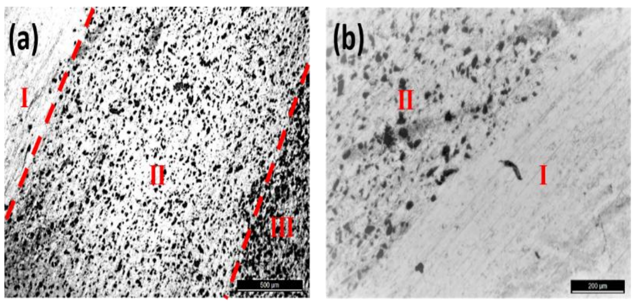

Fig.6: Microstructure of Al/ Al2O3 FG sample observed under optical microscope

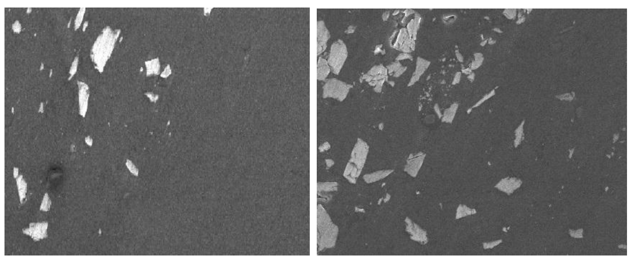

Fig.7: FESEM image of Al/ Al_2O_3 FG sample showing different layers.

2.2. Rapid Prototyping:

Such techniques also otherwise known as Additive Manufacturing and Solid free form fabrication where a product is designed using CAD software - the CAD data is then converted to triangulation language (STL) file – the STL file is fed to the RP machine where the STL file is sliced in to two-dimensional cross section profile – then the part building starts from the bottom most layer and the process continues with layer by layer addition. Then finally the part is removed and finishing touch is given [9,10]. As the finished product is built in a layered manner it has gained popularity as the new age technology and popular by the name Additive Manufacturing.

2.3. Additive Manufacturing:

Unlike the conventional machining process such as turning, milling, shaping or planning etc. where a part is produced from a stock by step wise removal of materials, the parts produced by additive manufacturing or layered manufacturing technique (LMT) are based on adding material layer after layer e.g. the **stereo lithography technique** (ref: Figure 8).

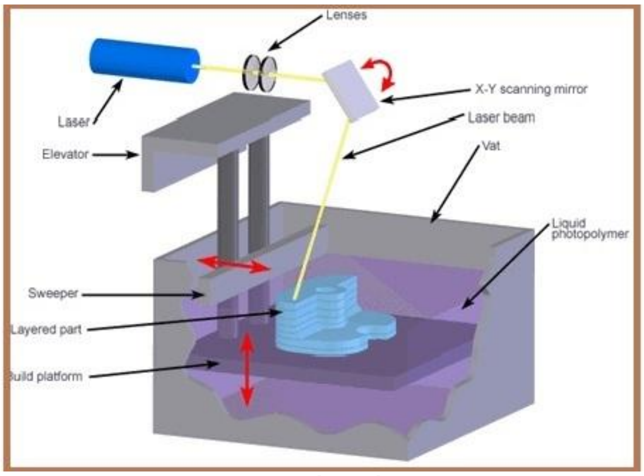

Fig.8: Stereo Lithography Process

3D CAD is a very powerful design optimization tool with which the product developer not only optimizes the design, simulates the process using simulation tools and removes all bottlenecks to shorten the lead time for the product. Such CAD software's does provide flexibilities in terms of concept modeling, develop virtual prototypes with acceptable tolerances in short span of time and when the software is interfaced with RP machines they are able to produce finished products that can go in to an assembly in a real time production line. With development of 3-D Metal printers it is now possible to produce metallic components in a very short span of time with all the advantages discussed above. The advantage that accrues from here is the reduced time to market for any new product. Such technologies allow the liberty for fast changes to design and flexibility in technical changes both from design as well as manufacturing point of view. LMT limits these changes to data and not hardware modifications.

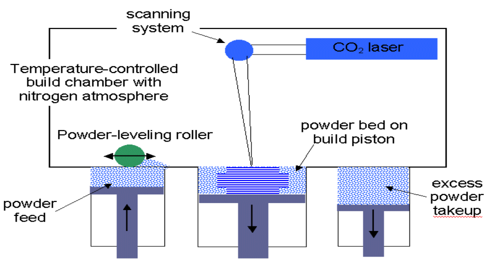

Fig. 9: Selective Laser Sintering Process

Fig10: 3-D Printing Process

Thus, quality improvement and product stabilization resulting from testing and field experience can still be introduced without incurring higher cost (say for changing tools or manufacturing processes etc.) [11]. During product realization stage using LMT, the process goes on automatically without any human intervention. Thus, as the number of materials to be used is increased or the material properties are improved for each layer, it implied that better quality physical prototypes are produced. Thus, gradually such processes are getting stabilized, leading to better quality products at short notices with better functional qualities, hence many small series, actual end production parts are being planned through layered manufacturing technology (Fig.9 and 10) nowadays or Additive Manufacturing [12, 13] or Rapid Manufacturing (RM). More and more researches are required to improve upon the SFF process performance through detailed characterization of FGMs so that a more detailed database is available for use and creation of better predictive model for proper control of processes. This will enhance the overall process performance, lower the cost of FGM and increase fabrication process reliability.

3. Researches in the Field of FGM:

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 detailed review on FGM performance was published in 2008 by Birman and Byrd, [14]. Shanmugavel et al [15] studied the fracture behavior of FGM. Considerable number of deliberations, studies, modeling, prototyping and validation studies on FGM [16, 17] have been carried out. Technologies like theoretical analysis, graphical modelling, computer aided designing, simulation modelling, finite element modelling, rapid prototyping, 3D printing have been put to good use for above purpose. This is not an end in itself and there are still many gaps or bottle necks that need to be identified and sorted out in terms of quality research to improve the overall processes, quality and reliability of FGM manufacturing.

4. Future Scope for FGM:

FGMs are counted among the best of advanced materials that are playing a vital role in revolutionizing the manufacturing world in the recent years but for a number of hurdles to be overcome on the way in order to realize this objective. Cost is a factor, with significant part of the cost used in processing the powder and in the methods of fabrication. Bulk production with quality and reliability are also the factors to be focused upon when opting for FGMs.

5. FGM Application Areas:

Aerospace: Due to the high temperature gradient withstanding capabilities, FGMs are in great demand for use as temperature shielding components in structures of aerospace applications, missile systems, nuclear power plants etc. [18, 19]. Conical shells and panels have a wide application in many aerospace vehicles which are increasingly made up of functionally graded materials. Structures like conical shells, panels have wide applications in aerospace vehicles which are gradually being mainly made up of FGMs. This implies FGM shell structures in general, and FGM conical shells and panels in particular require dynamic researches on account of both static and dynamic behaviors. 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 space craft, 'Orbiter'. Other possible uses include combustion chamber insulation in ramjet or scramjet engines. FGMs have lot of potential usage where the operating conditions are hostile like the spacecraft heat shields and the heat exchanger tubes.

Other Applications: Medicine: Bones and teeth are living tissues and are excellent examples of FGMs from nature [20, 21] and to replace such tissues, suitable well-suited materials are needed that would serve the purpose of the original bio-tissues. For dental and orthopedic applications FGM has proven to be blessing in disguise [23, 24].

Defense: Inhibiting the crack propagation is one of the most important characteristics of FGMs. This property makes them useful in defense application, as a penetration resistant material preferred for use in armored plates and vests that are bullet-proof [25].

Energy: Energy conversion devices are an area that has given FGMs a lot of scope to prove their utility. As thermal barriers, as shielding coating on turbine blades in gas turbine engine, FGMs are a proven material and score better in comparison to other conventional materials that are in use [26]. FGM also finds its application in many other fields and provides ample scope for new research with new hopes of a better tomorrow.

6. Conclusion:

Aerospace, automobile, medicine, sport, energy etc. are some of the key sectors that provide the scope for application of functionally graded materials. It is expected that the application of FGM would be growing further providing ample opportunities for further deliberations and research once the cost of powders, overall process cost are reduced to an affordable level and at the same time the fabrication process is improved. Considering the significance of FGMs and the opportunity for new developments, lots of efforts are being put up to improve the raw material processing, fabrication process and overall properties of the FGMs. Researcher should focus now in merging the modeling of FGMs with substantive experimental work. Experimental and theoretical studies of the FGMs are very significant and need further developments so as to seek the unknown and possible FGM properties for new potential applications of FGMs. Future applications require materials with extraordinary mechanical, electronic and thermal properties which can withstand hostile environmental conditions and are easily available at reasonable cost at the same time being environmentally friendly too.

Acknowledgement

a) The authors would like to acknowledge the help and support rendered by CSIR-IMMT, Bhubaneswar, Gandhi Institute For Technology, Bhubaneswar and Department of Mechanical Engineering, ITER, SOA Deemed to be University, in carrying out the experimental work in producing Al/Al2O3 FGM samples and subsequent tests.
b) The authors would also like to express their regards and gratitude for the expert suggestions guidance received from eminent scholars like Dr. B.K. Satapathy, Ex-Executive Director (R&D), NALCO, Bhubaneswar, Dr. T. K. Rout, Principal Scientist, TATA Steel, Kalinga Nagar, Jajpur and Dr. Nabnit Panigrahi, Dean Research, Gandhi Institute For Technology, Bhubaneswar during the conduct of the experiment and compilation of this technical paper.

References

[1] Yamanouchi M, Koizumi M, Hirai T, Shiota I. Proceedings of the First International Symposium on Functionally Gradient Materials. Japan, 1990.
[2] Rajat Gupta, Rohit Kumar, A.K. Chaubey, Shailesh Kanpara and S.S. Khirwadkar, "Mechanical and microstructural characterization of W–Cu FGM fabricated by one-step sintering method through PM route", IOP Conf. Series: Materials Science and Engineering 338 (2018) 012042 doi:10.1088/1757-899X/338/1/012042.
[3] A Tripathy, S.K. Sarangi, R.K. Panda, "Fabrication of functionally graded composite material using powder metallurgy route: an overview", IJMPERD, Vol. 7, Issue 6, 135-146, Dec 2017.
[4] Bryan Harris, Engineering Composite Materials, The Institute of Materials, London, 1999
[5] Partho Sarkar, Someswar Datta, Patrick S. Nicholson, "Functionally graded ceramic/ceramic and metal/ceramic composites by electrophoretic deposition", Composites Part B: Engineering, Volume 28, Issues 1–2, Pages 49-56, 1997.
[6] Lannutti JJ, "Functionally graded materials: Properties, potential and design guidelines", Compos. Eng. 4(1):81-94. 1994.
[7] Emilio Carlos Nelli Silva, Matthew C. Walters, Glaucio H. Paulino, "Modeling bamboo as a functionally graded material: lessons for the analysis of affordable materials", J Mater Sci, 41:6991–7004, 2006.
[8] Zhu J, Lai Z, Yin Z, Jeon J, Lee S, Fabrication of ZrO2-NiCr functionally graded material by powder metallurgy, Materials Chemistry and Physics, 68, p 130-135, 2001.
[9] B. Kieback, A. Neubrand, H. Riedel, Processing techniques for functionally graded materials Materials Science and Engineering A362 (2003) 81–105. Received in revised form 7 February 2003.
[10] J Rix, Dr. Stefan Haas, J. C. Teixeira, Virtual prototyping: virtual environments and the product design process: proceedings of the IFIP WG 5.10 workshops on virtual environments and their applications and virtual prototyping, 1994, Springer international publishing, 1995.
[11] M. A. Boboulos, CAD-CAM & Rapid Prototyping Application Evaluation, PhD & Ventus Publishing Aps, accessed online on 1st March 2012, available at www.bookBoom.com.
[12] K. G. Prashanth, L. Löber, H-J. Klauss, U. Kühn, J. Eckert, "Characterization of 316L steel cellular dodecahedron structures produced by selective laser melting Technologies," Vol. 4 (2016) 34.
[13] S. Scudino, C. Unterdoerfer, K. G. Prashanth, H. Attar, N. Ellendt, V. Uhlenwinkel, J. Eckert, Additive Manufacturing of Cu-10Sn bronze, Materials Letters, 156, p202-204, 2015.
[14] Victor Birmana, Larry W. Byrdb, "Stability and natural frequencies of functionally graded stringer-reinforced panels, Science Direct, Composites, Part B 39, p816-825, 2008.
[15] P. Shanmugavel, G. B. Bhaskar, M. Chandrasekaran, P. S. Mani and S. P. Srinivasan, "An overview of fracture analysis in functionally graded materials," European Journal of Scientific Research, vol.68 No.3, pp. 412-439, 2012.
[16] Victor Birman, "Modeling and Analysis of Functionally Graded Materials and Structures", DOI:10.1007/978-94-007-2739-7_574, January 2014.
[17] Ankit Gupta, "Recent development in modeling and analysis of functionally graded materials and structures", Progress in Aerospace Sciences 79, DOI:10.1016/j. paerosci.2015.07.001i, 2015.
[18] L. Marin, "Numerical solution of the Cauchy problem for steady-state heat transfer in two dimensional functionally graded materials," International Journal of Solids Structures, vol. 42, pp. 4338-4351, 2005.
[19] K M Liew, S Sivashanker, X Q He and T Y Ng, K M Liew et, "The modeling and design of smart structures using functionally graded materials and piezoelectric sensor/actuator patches", Smart Mater. Struct. 12 647. doi:10.1088/0964-1726/12/4/316, 2003.
[20] W. Pompe, H. Worch, M. Epple, W. Friess, M. Gelinsky, P. Greil, U. Hempel, D. Scharnweber, K. Schulte, "Functionally graded materials for biomedical applications", Materials Science and Engineering A362, p 40–60, 2003.

[21] Sadollah Ali, Bahreininejad Ardeshir, “Optimum Functionally Gradient Materials for Dental Implant Using Simulated Annealing”, IN Tech, p211-238, 2012.
[22] Mehdi Mehrali, Farid Seyed Shirazi, Mohammad Mehrali, Hendrik Simon Cornelis Metselaar, Nahrizul Adib Bin Kadri, Noor Azuan Abu Osman Dental implants from functionally graded materials, journal of biomedical materials research, Vol. 101A, Issue 10, pp 3046-3057, 2013.
[23] Hedia H. S., El-Midany T. T., Shabara M. A. N., Fouda N., “Development of cement less metal backed acetabular cup prosthesis using functionally graded material”, Int J Mech Mater Des Vol 2:p259–267,2005.
[24] Tawakol A. Enab A, “Comparative study of the performance of metallic and FGM tibia tray components in total knee replacement joints”, Computational Materials Science, Vol 53, p94–100, 2012.
[25] Lu, M. Chekroun, O. Abraham, V. Maupin and G. Villain, “Mechanical properties estimation of functionally graded materials using surface waves recorded with a laser interferometer”, NDT & E International, Volume 44, Issue 2, Pages 169-177, 2008.
[26] Eckhard Mueller, C. Drasar, J Schilz, W.A Kaysser, “Functionally Graded Materials for Sensor and Energy Applications”, Materials Science and Engineering A 362(1-2):17-39, DOI: 10.1016/S0921-5093(03)00581-1, 2003.