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FUNCTIONALLY GRADED MATERIAL BY ADDITIVE MANUFACTURING

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ABSTRACT: Functionally graded material (FGM) is a new generation of engineered material with changes in the properties of material by varying structural design or material composition. The fabrication of FGM by conventional techniques mostly offer control in varying composition and hardly offer control in varying structural design. The flexibility of structural design provided by additive manufacturing such as selective laser melting (SLM) makes it an outstanding technique to fabricate FGM. In this research, an overview of FGM fabrication techniques was presented covering both conventional techniques and various additive manufacturing techniques. On the other hand, fabrication of a FGM with varying structural design was demonstrated using SLM technique and titanium alloy as material. The structural design fabricated by SLM was periodic cellular structures with cubic unit. To obtain FGM, the structure was varied by change in strut thickness continuously and linearly in single direction. Results showed that the complex design was successfully fabricated by SLM and achieved nearly full-dense strut for the fabricated part.

KEYWORDS: 3D printing, additive manufacturing, functional gradient, Selective Laser Melting, lattice structure

INTRODUCTION

Functionally graded material (FGM) is a kind of material in which the composition and/or the structure gradually change over the volume, resulting in corresponding changes in the properties of the material. There are different classifications of FGM according to the nature of gradient. For example, transition from dispersed to interconnected second phase structure, layered graded or continuously graded structure according to Miyamoto et al. (1999). There are also gradients by volume fraction, shape, orientation or size according to Khan (2015). FGM could also be classified into gradient in composition either with or without diffusion of secondary material, gradient in structure and gradient in porosity/density. The concept of FGM is applicable to many fields ranging from aerospace, engineering parts, biomaterials and commodities. One example in aerospace application is the use of graded ceramic/metal at the superstructure/tile interface for thermal protection during re-entry into Earth's atmosphere studied by Cooley (2005). Various techniques have been utilized for fabricating FGM. In this study, an overview of FGM fabrication techniques will be presented covering both conventional techniques and various additive manufacturing techniques. In addition, fabrication of FGM with variation in structural design was demonstrated using SLM technique and titanium alloy (Ti-6Al-4V) as material.

OVERVIEW OF FGM FABRICATION TECHNIQUES

The techniques of fabricating FGM are summarized in Figure 1 together with issues associated with each technique. The techniques on the left side of the figure which surrounded by dash line are conventional techniques according to Miyamoto et al. (1999). It can be seen from the figure that there are many ways to fabricate FGM with change in composition using conventional techniques but only few methods could achieve gradient in porosity and there is precision/shape limitation in controlling the graded porosity with conventional techniques. A more state-of-the-art techniques to fabricate FGM are sol-gel process, superplastic forming with diffusion bonding, and additive manufacturing. Sol-gel process is a fiber stacking and chemical method that uses additives, chemicals, and hot-pressing to fabricate graded ceramic matrix composites in an innovative way. Superplastic forming with diffusion bonding uses superplastic metal or ceramic as basic material or as an insert in the joining area. The temperature and pressure required for bonding during the process are reduced due to low strain rate. It provides flexibility in design, reduces mechanical joints and used primarily for manufacturing aircraft parts from titanium alloys. Additive manufacturing is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Complex FGM geometry either with composition change, structural change or porosity change could be achieved by various techniques of additive manufacturing process. The flexibility in the structural design of material provided by additive manufacturing makes it an outstanding technique to fabricate FGM, especially for gradient in structure, porosity and density. FGM made by conventional techniques possess relatively simple geometries, limited design freedoms, and consequently lack advanced functionality to meet the requirements of many applications. Advanced and complex 3-dimensional periodic cellular structures that mimic natural structures with controlled density and strength are achievable with additive manufacturing. This technique also allows FGM concept with lightweight structures that closer to an “optimum” design to be created rather than settling for a compromise due to manufacturability constraints.

FABRICATION OF FGM BY ADDITIVE MANUFACTURING

Different additive manufacturing processed were researched to fabricate FGM. Among them, fused deposition process (FDM) and selective laser sintering (SLS) are used for polymer materials while laser engineered net shaping (LENS), selective laser melting (SLM) and electron beam melting (EBM) are used for metal materials.

Kalita et al. (2003) fabricated scaffolds with different complex internal architectures and controlled porosity via FDM process using polypropylene polymer and tricalcium phosphate ceramic. Uniaxial compression tests on cylindrical porous samples with an average pore size of 160 μm and varying porosity (36%, 48% and 52%) showed the best compressive strength of 12.7 MPa existed in sample with 36% porosity. These samples were proven to be nontoxic with excellent cell growth during the first two weeks of in vitro testing.

Chung & Das (2008) studied SLS process to fabricate functionally graded polymer nanocomposites of nylon-11 filled with 0–10% by volume of 15 nm fumed silica nanoparticles. The tensile and compressive properties exhibited a nonlinear variation as a function of filler volume fraction. Study of SLS process was also done by Sudarmadji et al. (2011) for functionally graded scaffolds with stiffness gradient that mimics the native bone by controlling their structure

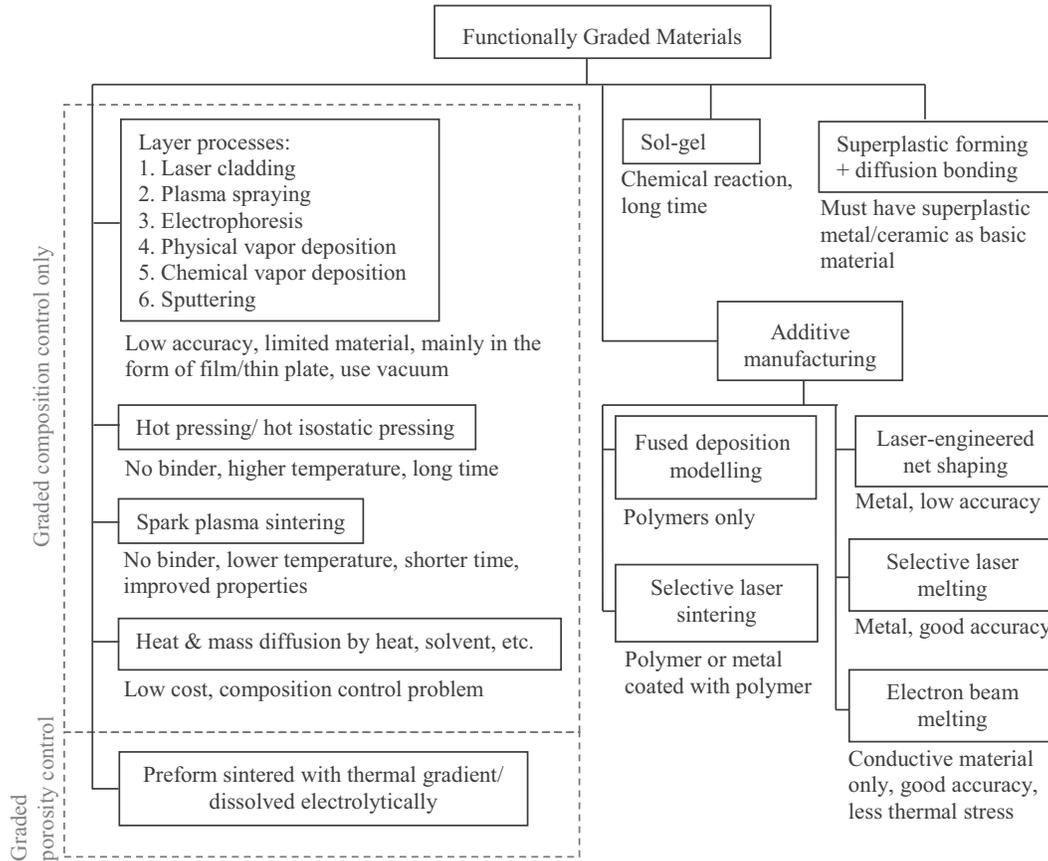


Figure 1. Summary of various FGM fabrication techniques

and porosity. Polycaprolactone was chosen as material. Scaffolds with different structural configurations were designed using CASTS consisting of 13 different polyhedral units that can be assembled into scaffold structures. Through compression tests on the fabricated parts, the CASTS database relating porosity and corresponding mechanical stiffness has been completed. The range of stiffness closely matches the cancellous bone in the maxillofacial region. Cytotoxicity assessment showed that SLS process does not induce toxicity of the scaffolds.

Mumtaz & Hopkinson (2007) studied SLM process for functionally graded specimens of super nickel alloy and ceramic compositions with discrete changes between layered compositions. The graded specimens initially consisted of 100% Waspaloy ® with subsequent layers containing

increased volume compositions of Zirconia (0–10%). Specimens were examined for porosity and microstructure. It was found that specimens contained an average porosity of 0.34% with a gradual change between layers without any major interface defects. Another research by Hazlehurst et al. (2014) confirmed that SLM can repeatedly manufacture a FGM that is 48% lighter and 60% more flexible than a traditional fully dense femoral stems as an orthopaedic implants. The FGM investigated were three separate designs incorporating square pore cellular structures of varying density. However, there are concerns associated with the repeatability of the manufacturing process for producing stems with cellular structures that incorporate strut sizes, which are equal to or less than 0.5 mm. Technologies such as micro computed tomography scanning would be needed to investigate the reasons associated with this failure. Niendorf et al. (2014) used advanced two laser SLM facility and 316 L powder as material to create FGM with different local functionalities by varying process parameters. Clear local differences in mechanical properties were obtained. Low et al. (2014) has shown that the density of Ti-6Al-4V alloy solid could be varied by manipulating SLM process parameters. The variation of density could provide change in material property to obtain FGM. In the same study, a FGM sample with lattice structure was also fabricated where the unit size of repeating unit was increased in stepwise manner.

Zhang et al. (2008) successfully fabricated FGM with composition change from pure titanium to 40 volume percentage of titanium carbide (TiC) with LENS process by adjustment of process parameters and real-time variation of the material feeding ratio during process. The tensile strength changed marginally with TiC content, while the ductility displays a sharp reduction with increase in TiC addition. Another study on LENS process by Durejko et al. (2014) demonstrated the fabrication of thin wall tubes Fe₃Al/SS316L FGM with composition change perpendicularly to the wall of the tube. The FGM tubes were characterized by a smooth transition between two components, a high metallurgical quality and a good reproduction of the designed model's shape.

In a study on EBM process done by Yang et al. (2007), titanium/molybdenum FGM with high temperature resistant was fabricated. The part showed fine appearance and good integrated interface. EBM process has also studied by Parthasarathy et al. (2011) to fabricate FGM with periodic cellular structures specifically targeted for biomedical applications. The effective stiffness values and compressive strength values of the fabricated part were substituted for simulation of biomechanical performance of patient-specific implants. The results show the compatibility and matched functional performance characteristics of highly porous parts at a safety factor of 5 and an effective reduction in weight. The fabricated FGM would have mechanical properties equivalent to the part they replace and restore better function and esthetics as against the currently used methods of reconstruction.

The reported FGM fabricated by additive manufacturing show the potential of the technique. However, there are challenges in additive manufacturing to be overcome. For instance, material and energy consumption of support structure which is required for anchoring fabricated parts to a substrate, and to prevent overhang and floating surfaces from curling up away from the correct geometry. According to Hussein (2013), minimum wall thickness and internal geometries with very fine structures below 1 mm still are a technical challenge. The manufacturability is an important factor for the selection of the cell type, size, build orientation, and density of cellular structure for specific applications. Specific anisotropy might exist within fabricated part which depends on build direction of the part. Metal which is cooled from high temperatures to room temperature have a tendency to deform during the process due to thermal stresses gradients generated. Thermal stresses could lead to part distortion, initiate fracture, and unwanted decrease

in strength of the part. Post processing by heat treatment could be one of the solutions. Support structure could also be function to dissipate heat from the newly melted layer and restrain part deflection caused by thermal stresses. Thermal stress problem is not severe in the case of EBM process. However the surface quality of part from EBM process is lower than SLM process.

LATTICE STRUCTURED FGM BY SLM TECHNIQUE

SLM process was investigated for fabricating a FGM design with gradient change in structure using Ti-6Al-4V alloy powder as material. The FGM design is a lattice structure with cubic shape tilted at 45 degree as repeating unit and the strut thickness was increased continuously and linearly in one direction throughout the sample as shown in Figure 2 (a). The structural change in this design is continuous gradient as opposed to many literatures with stepwise change or change layer by layer. 3-matic software was used to create the design and the saved file was processed in Magic software before sending to SLM machine for printing. The SLM machine used was SLM 250 HL (SLM Solutions GmbH). During printing, the metal alloy powder was spread and then scanned by laser layer by layer. Metal powder exposed to laser melted totally and fused together to form a part. Optimized process parameters such as laser power, laser speed, and hatch spacing referenced from Low et al. (2014) were used to ensure full density at the solid portion of fabricated part. Figure 2 (b) shows the fabricated FGM. The shape and structure of the fabricated FGM were exactly same as designed and the continuous gradient change in strut thickness was smooth under visual observation. Density measurement with device using Archimedes' principle showed that the sample was close to full density.

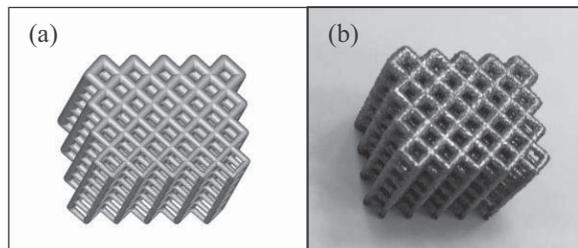


Figure 2. (a) FGM design in software, (b) FGM fabricated by SLM technique

CONCLUSION

Many conventional techniques are available to fabricate FGM with change in composition but only few of them could achieve gradient in porosity and there is precision/shape limitation in controlling the graded porosity with conventional techniques. Complex FGM geometry either with composition change, structural change or porosity change could be achieved by various techniques of additive manufacturing. The advantage of controllable FGM gradient by SLM technique which is one of the laser-assisted additive manufacturing was demonstrated in this study. In view of the huge potential of additive manufacturing to fabricate FGM for many applications, more research on the manufacturability and mechanical behavior of fabricated part shall be carried out for selection of optimal process.

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