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ScienceDirect

Procedia Manufacturing 10 (2017) 866 – 875

Procedia MANUFACTURING

45th SME North American Manufacturing Research Conference, NAMRC 45, LA, USA

# Fabrication of Functionally Graded Porous Polymer Structures Using Thermal Bonding Lamination Techniques

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## Abstract

Functionally graded porous materials (FGPMs) are porous structures with porosity gradient distributed over volume. They have many potential applications in aerospace, biomedical, and other industries. Despite significant efforts have been made to fabricate FGPMs, the existing manufacturing techniques are either complex, expensive, unable to control exact porosity distribution, or unable to create closed cell structures. This paper presents an additive approach for fabrication of polymer FGPMs with both closed cell and open cell structures using thermal-bonding lamination techniques. Under applied compressive load, controlled heating, and appropriate holding time, it was shown that this thermally induced bonding technique can bond layers of polymer sheets to create porous three-dimensional objects. The effects of various factors on the bonding shear strength were investigated. It was found that the bonding strength can be controlled by properly setting the pressure, temperature, and time in the process. The fabricated FGPMs specimens with different porosity configurations were further characterized using compression test in the normal and transverse directions. The results show that the developed techniques can be used to obtain FGPMs with various effective moduli.

Peer-review under responsibility of the organizing committee of the 45th SME North American Manufacturing Research Conference

*Keywords:* additive manufacturing; functionally graded porous materials; thermal bonding; lamination

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Peer-review under responsibility of the organizing committee of the 45th SME North American Manufacturing Research Conference
doi:10.1016/j.promfg.2017.07.073

## 1. Introduction

Functionally graded materials (FGMs) are composite materials formed of two or more constituent phases with the variation in composition and structure gradually over volume, resulting in corresponding changes in the properties of the material [1]. FGMs are usually associated with particulate composites. They have received great attention because there are certain desirable features of each constituent phases, and they can be designed for specific function and applications [2]. Functionally graded porous materials (FGPMs) are materials with porosity gradually changing throughout their volume. The pores are distributed in the base material with variation in porosity. The variation of porosity may be due to density change or size change of the pores. Based on the cell structure, FGPMs can be open cell or closed cell structures. In open cell structures, the pores are interconnected; while in closed cell structures, each cell is enclosed and isolated by the base material. The gradual change of porosity can impart desirable properties. Examples of nature FGPMs include bamboo with density gradients along the radial direction in its cross section [3], human cancellous bone which is sponge-like cellular structure [4], banana peel [5], and elk antler [6], etc. Artificial FGPMs, such as biomedical implants [7, 8], cushioning materials [9], filtration materials, drug delivery devices [10], and permeable interlocking pavement, etc, are also widely used in industries and daily lives.

Various approaches have been used to manufacture polymeric porous materials. *Gas foaming* uses supercritical fluid as a blowing agent to generate polymer foams. Based on the *phase separation* techniques, immersion precipitation, thermally induced phase separation, and chemically induced phase separation techniques have been used to produce polymer membranes and foams with micro-porous structures [11]. *Solvent casting and particle leaching* is commonly used to make scaffold where the solvent is evaporated followed by particle leaching when the material is immersed in solution to create porous polymeric materials [12]. Other processing techniques, such as emulsion freeze drying, templating, and molecular imprinting, have also been developed. These methods, however, are relatively complicated since they require mold, machine, and/or foaming agents. More importantly, the exact pore size, overall porosity, morphology, and the porosity gradient are hard to control when using these processes.

Due to their ability to produce components with remarkable complexity in material and geometry, Additive Manufacturing (AM) has gained significant attention in recent years. Based on 3-D models generated from computer software, the porous material can be fabricated with a better control of the micro-scale structure, e.g. dimension, size of pore, porosity, morphology, and overall shape, compared to the conventional technologies.

Jande *et al.* [13] prepared uniform and graded porous polyamide structures and polyamide-epoxy composites using *Selective Laser Sintering* (SLS). The graded porosity can be well controlled. Polymeric matrix drug delivery devices were developed by Leong *et al.* [10], and the work focused on studying the effects of SLS process parameters, such as laser beam power and scanning speed, on the resulting porosity and drug release rate. Bioresorbable and biodegradable polymer materials such as polycaprolactone were adopted in order to potentially apply to bone and cartilage scaffolds [14, 15]. Other efforts include studying the effects of laser processing parameters and thermal control conditions on the material properties [16] and exploration and investigation for more available and suitable materials [17].

*Stereolithography* (SLA) builds parts layer by layer using lithographic methods, e.g. curing a photo-reactive resin with a UV light through photopolymerization. The materials used are mostly polymers, wax or wax compounds which have to be reactive resins. Liebschner [18] optimized the bone scaffold for load bearing application, and Yu [19] used SLA to fabricate functionally graded shape memory polymer which is able to response quickly to an external stimulus, and return to a certain configuration in a controlled shape changing fashion.

Kalita *et al.* [8] used *Fused Deposition Modeling* (FDM) to process polymer-ceramic composite scaffolds with controlled porosity. The porous structure was proved to be a good bone graft with its biological, mechanical, and physical properties aligned well with requirements. Yu *et al.* [20] proposed a hybrid bioprinting system to process scaffold-free cellular constructs for tissues and organ models using two micro-nozzles. Other AM processes such as Selective Laser Melting (SLM), Electron-beam Melting (EBM) have also received extensive attention.

An inevitable issue involved in all the above-mentioned AM techniques, however, is that they rely on either a different supporting material (FDM) or the constituent/part materials (SLS, SLA, SLM, EBM) to fill in space when fabricating porous parts. Some of the filler materials are hazardous or contain harmful chemical when disposal. It is also reported that the material consumption for the purpose of filling in space can be greater in volume and in cost than the actual part. More importantly, it is time-consuming to clean the filler material especially when the pore size