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Full Length Article

Quantifying fatigue property changes in material jetted parts due to functionally graded material interface design

Dorcas V. Kaweesa[a], Nicholas A. Meisel[b,*]

[a] Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA 16802, USA
[b] School of Engineering Design, Technology, and Professional Programs, The Pennsylvania State University, University Park, PA 16802, USA

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ABSTRACT

The capability of Additive Manufacturing (AM) to manufacture multi-materials allows the fabrication of complex and multifunctional objects with heterogeneous material compositions and varying mechanical properties. The material jetting AM process specifically has the capability to manufacture multi-material structures with both rigid and flexible material properties. Existing research has investigated the fatigue properties of 3D printed multi-material specimens and shows that there is a weakness at multi-material interfaces. This paper seeks to, instead, investigate the effects of gradual material transitions on the fatigue life of 3D printed multi-material specimens. In order to examine the fatigue life at the multi-material interface, stepwise gradients are compared against continuous gradients created through voxel-based design. Results demonstrate the effects of different material gradient patterns and different material transition lengths on the fatigue life of multi-material specimens. In addition, the behavior of individual material composites is studied to confirm how gradient designs based on different material compositions affect their material properties.

1. Introduction

Additive Manufacturing (AM) is a process that involves producing three dimensional parts by joining materials in a layerwise manner. AM has a number of advantages over traditional manufacturing processes because it offers vast geometric and material design freedom [1]. Currently, the three commercial AM processes capable of processing multiple materials in a single build are material extrusion, directed energy deposition (DED), and material jetting. The scope of this research focuses on the multi-material capabilities offered by material jetting, specifically the PolyJet process, due to its voxel-based design and manufacturing abilities. The PolyJet process involves the selective jetting of liquid-based droplets of photopolymer materials which are cured by an ultraviolet light [2]. In addition, the PolyJet process allows manufacturers to finely control multiple material compositions through voxel-based deposition, whereby one material is gradually suspended within the matrix of another material across a structure's volume. This aspect can lead to the creation of functionally graded materials (FGMs). FGMs are heterogeneous materials consisting of two or more constituent materials that spatially vary in their material composition across the volume of a structure [3–5], as seen in Fig. 1a. In general, FGMs can be categorized into either continuous gradients or stepwise gradients as shown in Fig. 1b. Continuous gradients have smooth transitions between their material compositions with respect to the position of the gradient within a structure. Stepwise gradients have discontinuous material compositions that form multilayered structures with material interfaces existing between discrete layers [3]. When voxel-based patterning is used, a continuous gradient could inherently be considered to be stepwise at the microscale, since no material mixing is taking place. However, for this research, stepwise gradients are categorized based on their large scale and visible gradient transitions at the material interfaces whereas the regions with continuous gradients have smooth non-visible gradient transitions. While stepwise gradients are feasible with traditional manufacturing techniques, continuous gradients may offer better performance when fabricated using the PolyJet process.

The ability to create functionally graded materials involves selecting appropriate material compositions to successfully attain desired performance based on the unique material properties of the base materials [6]. Researchers have looked into spatially varying material compositions and developing system-type models to evaluate FGMs designs. In particular, Kawasaki and Watanabe [7] and Doubrovski [8] used function-based representations and mathematical expressions respectively to design gradients of materials. By defining the spatial distribution of materials within a specified volume using voxel-based representations, the microstructure and overall structural composition

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* Corresponding author.
E-mail address: nam20@psu.edu (N.A. Meisel).

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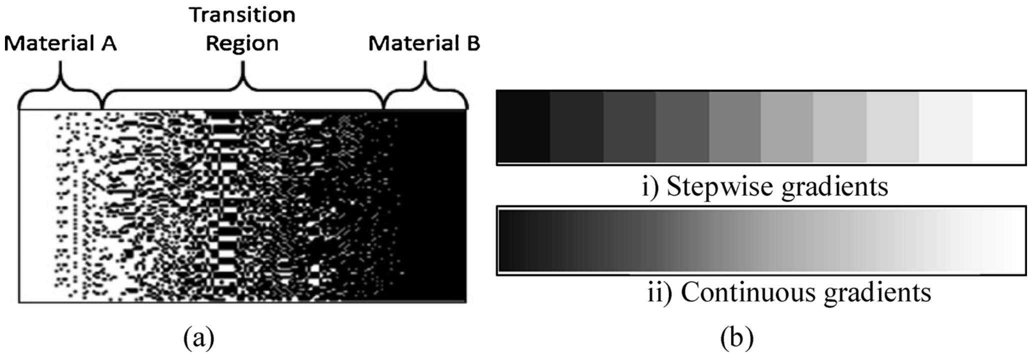

Fig. 1. (a) Structure showing a functional gradient between material A and material B and (b) categories of functional gradients.

was defined to develop a functionally graded structure.

Researchers have also looked into AM processes that provide better opportunities for manufacturing functionally graded structures. Stoner et al. [9] used the material extrusion process to manufacture bi-continuous geometries, a gyroidal mesostructure and a binary material interface with FGM compositions. The design process of the material compositions involved varying the volume fraction of the FGM interface. Preliminary results showed that the increased complexity of the gyroidal mesostructure provided good material gradient fusion hence increased strength. Garland and Fadel [10] also used the material extrusion process, specifically the Big Builder 3D printer, to develop functionally graded structures. The quality of the structure obtained from combining two materials was found to be unsatisfactory due to the printer's limited capability in automatically mixing the material compositions during deposition. In addition, obtaining an optimal toolpath to produce structurally robust functionally graded structures, especially in the XY orientation, proved to be rather difficult to achieve. While these research studies show the possibility of developing functionally graded structures using the material extrusion process, they also show that additional research work is still required due to the complexity experienced in the actual generation of FGM compositions. Conversely, the DED process has the ability to vary the compositions of material in either wire or powder form during actual deposition and still maintain full density [11]. Shin et al. [12] also confirmed this aspect by printing a functionally graded metal part with varying material compositions of copper and nickel at the exact point of material deposition. However, the material deposition approach of the DED process lacks the capacity for fine voxel-based control of FGM patterns. Research studies by Udupa et al. [13], Hegab [14], as well as Gupta and Talha [15] also looked into the various developments regarding the state of modeling and analyzing FGMs and structures with the powder based AM processes.

Whereas existing research studies have mainly focused on developing optimum designs for functionally graded structures (as in Refs. [7,8]), present research involving FGM processing with the PolyJet process focuses predominately on its general multi-material opportunities toward the creation of flexible structures. For instance, an experiment performed by Bruyas et al. [16] successfully used PolyJet process to create a novel design of a multi-material compliant joint in order to improve the stiffness properties of the joints and maximize the range of motion. In addition, research conducted by Gaynor et al. [17] also focused on using the PolyJet process to fabricate an optimized multi-material compliant mechanism. With a systematic design process involving the use of appropriate topology optimization approaches and algorithms, the authors were able to show how the PolyJet process provides more robust solutions to multi-material topology optimization problems.

Furthermore, Moore and Williams [18,19] looked into characterizing the fatigue life of specimens with a single discrete elastomeric material interface manufactured using the PolyJet process. They sought to predict the expected lifespan of the specimens based on a series of fatigue tests. Results showed that fatigue life in the elastomeric region improved for specimens tested at low strain rates. However, they also noted high levels of variability in specimen fatigue life due to unpredictable failure at the multi-material interface. The work by Moore and Williams is significant to the research presented in this paper in that the authors are more interested in looking at the impact of graded multi-material interfaces rather than a single elastomeric material interface to improve the fatigue life and possibly eliminate the variation observed in interfacial failure. Therefore, the main objective of this research work is to investigate the effects of different multi-material gradients types distributed over different material transition lengths on the fatigue life of multi-material specimens at (1) a constant volume and (2) a constant length of a selected flexible material. The work presented in this research will help determine whether or not varying material compositions of FGMs manufactured using the PolyJet process will improve the fatigue life of specimens with either continuous or stepwise gradients.

2. Design and experimental approach

To further understand how gradient-based materials operate, this work aims to determine an efficient way to design and distribute multi-materials particularly FGMs in order to maximize fatigue life for a desired performance and reduce premature failure. In summary, this research seeks to answer the following questions:

1. How does the length of the material transition within a specified region affect the fatigue life of multi-material parts?
2. Will continuous gradients offer a better advantage on the fatigue performance of printed multi-material parts compared to stepwise gradients?
3. How are the properties of different material composites affected by the individual materials in their compositions when a color-based dithering approach is used to define the FGM pattern?

2.1. Experimental design

In order to answer the presented research questions, a design of experiment approach was used with printed multi-material specimens to ensure systematic fatigue testing procedures. The specimens used for this study were designed according to ASTM D4482-11 [20]. Additional round beaded edges were designed and the length of the grip (rigid material) region was increased so that the specimens fit securely into a set of special grips during fatigue testing (Fig. 2).

In terms of material distribution, selected material compositions of a rigid material, VeroCyan (VC) used in the Objet350 Connex3 printer were distributed over a length of 25 mm in the material gradient transition region, in addition to a flexible material, TangoBlackPlus (TB+) for two instances: (1) a constant volume and (2) a constant length. A