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Analytical and experimental investigation on elastic modulus of reinforced additive manufactured structure

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ABSTRACT

Additive Manufacturing (AM) technique has been utilized in a variety of engineering applications because of its desirable characteristic of mass customized manufacturing. Polyjet 3 Dimensional Printing (3DP) is one among the various AM techniques which is well known for fabrication of part with multiple materials. Meanwhile, strength and stiffness of polyjet 3DP part is typically less and hence it is difficult to use it for engineering applications. To maximize polyjet 3D printed part stiffness, this study explores the novel methodology by incorporating high strength material among the multi materials as reinforcement in Additive Manufactured Multi Material (AM MM) structure. Uni-axial tensile test and fracture surface analysis over reinforced AM structure was carried out to investigate the influence of reinforcement and its orientation with respect to loading direction. The experimental result shows that addition of reinforcement enhanced the elastic modulus significantly as well as improvement in elastic modulus varies between 6.79% and 21.03% with respect to reinforcement orientation. Along with this, we have proposed simpler analytical method based upon Rule of Mixture (RoM) equation to predict the elastic modulus of reinforced AM structure. Comparison of the analytical method results with the experimental results implies that there is a good agreement between them. Methodology proposed in this work could be very useful in the cases of predicting strength of reinforced AM structure for engineering application.

1. Introduction

Additive manufacturing is emerging as a key manufacturing process, in which parts are fabricated by adding the material layer by layer as opposed to material removal principle in traditional manufacturing process such as turning, and drilling. AM techniques works by integration of laser, photochemistry, sintering and CAD [1,2]. Additive manufacturing is defined by American Society for Testing and Materials (ASTM: F2792-12a) as "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining". Adding material instead of removing it, results in fabrication of complex part with geometrically optimized, light weight, heterogeneous metal and polymer parts that offer same functionality as their traditionally machined counterparts, with little to no material waste [3,4].

Recent developments in additive manufacturing technology for Multi-Material (MM) processing lead to fabrication of AM component with heterogeneous material distribution. In Additive Manufactured Multi-Material (AM MM) structure softer constituent is referred as "matrix" and harder constituent is referred as "reinforcement". Development of reinforced AM structure may result in improvement of mechanical properties, additional functionality and design freedom for product development. And also investigation on MM structure like reinforced structure which is fabricated using additive manufacturing technology has paid much attention recently by several authors [5–7]. From literature it was observed that MM structure have been manufactured in additive manufacturing process in three approaches: (i) Homogeneous AM porous structure was infiltrated with secondary material, (ii) material was feed to AM machine as a blend of two materials and (iii) as part and support material deposition, two materials were successively spaced in an alternate layer or within a layer [8]. Other than the above motioned approaches, the MM structure can be fabricated using AM techniques either by part build strategy (i.e. CAD modelling) or by modifying the construction of AM machine (i.e. Material delivery system). However, method of fabricating MM structure through build strategy is cost effective compares to modification in machine construction. Therefore it is worthwhile to develop CAD model development strategies for fabrication of AM MM structure. This work presents a novel build strategy for fabrication reinforced AM structure.

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Additionally, from design engineer's point of view, mechanical properties such as elastic modulus, creep and fatigue strength of reinforced AM structure is highly required for new product development and prototyping activity. Among above mentioned mechanical properties, prediction of elastic modulus of reinforced AM structure is essentially focused in this work. Because elastic modulus is more related to failure mechanism that controls the failure of structure under uni-axial loading. Prediction of elastic modulus of AM structure through experimentation was robust [9,10], since it was orthotropic in nature. However, mechanical properties such as elastic modulus, shear and tensile stress of laminated reinforced composites were analytically determined through model such as Rule of Mixture (RoM) equation [11]. Laminated reinforced composite usually fabricated by "layer by layer" addition of laminate as similar to fabrication principle of additive manufacturing process. Because of their similarity in their manufacturing procedures, this paper has explored the use of RoM method to determine elastic modulus of reinforced AM structure. RoM is based on the properties of the constituent matrix and reinforcement materials as well as reinforcement volume fraction. From literature it was observed that few researchers have made attempts to determine the mechanical properties of AM component using RoM model. Even in these studies, AM structure considered for investigation was restricted to single material like plastics, metals or ceramics [12,13]. In this article we have explored the possibility of using RoM approach for predicting the elastic modulus of AM structure with multiple materials.

In the following subsections, geometric modelling, the principle of the additive manufacturing method and materials used for fabrication of reinforced AM structure are first presented and discussed. Then fabricated AM structures were subjected to uni-axial tensile test to determine its elastic modulus and influence of reinforcement on its strength. And also elastic modulus of reinforced AM structure was determined analytically using RoM model. Elastic modulus evaluated using RoM model was compared with experimental result to illustrate the feasibility and the stability of the present approach. Both experimentation and analytical method shows significant improvement in elastic modulus of reinforced AM structure, which is advantageous for fabrication of form, fit, and functional prototypes through additive manufacturing techniques. Mechanism behind improvement in modulus has been investigated using macroscopic approaches over fracture surface analysis. Finally, conclusion and some future research scope in reinforced AM structure have been discussed.

2. Experimentation

2.1. Modelling

To extend the capability of AM process for fabrication of reinforced AM structure, CAD model with appropriate information, such as reinforcement distribution and its composition is necessary [14]. Modelling of MM structure such as functionally graded structure and randomly oriented multi-material structure have been extensively studied by many researchers [15–17]. However, uni-directional reinforcement structure had superior mechanical properties in loading direction as compared to randomly oriented and graded reinforcement [18], so in this work directional reinforcement were considered for AM structure fabrication. For modelling of uni-directionally reinforced AM structure simple addin module was developed in CATIA V5 using CATIA VB SCRIPT. With this addin module, solid CAD model was developed with cylindrical shape reinforcement oriented at 0°, 45°, 90° with respect to loading direction. For descriptive purpose hereinafter AM structure with reinforcement oriented at 0°, 45°, 90° were respectively described as longitudinal, inclined and transverse reinforced AM structure. Diameter of cylindrical reinforcement was considered as 0.5 mm for all reinforced AM structure. Since 0.5 is the minimum wall thickness or feature width which could be manufactured in AM process (polyjet 3DP) considered for reinforced AM structure fabrication [19]. Reason behind selection of polyjet 3DP process for fabrication of reinforced AM structure was discussed under Section 2.2. Volume of reinforcement for all reinforced AM structure was considered as 10%. Fig. 1b shows uni-directionally reinforced dumbbell shape CAD model according to the dimensions of ASTM: D638 as shown in Fig. 2a for tensile test, The developed CAD model was exported as *.stl* (Standard Triangulation Language) format, which is a *defacto* standard for AM process [20]. Fig. 1a shows assembled and exploded view of transversely reinforced model, in which matrix and reinforcement model was exported to AM machine as two separate *.stl* file and respective materials were assigned to them before fabrication. Procedure described above was repeated for modelling of longitudinal and inclined reinforced structure.

2.2. Methods and materials

Polyjet 3DP process was chosen to fabricate reinforced AM structure; because of its polymerization technique which allows printing of two types of polymers simultaneously in well controlled manner [21]. Polyjet 3DP is a hybrid process of AM techniques (3D Printing (3DP) and sterolithiography (SLA)) where advantages of both techniques such as (i) fabrication of complex part in high speed with multiple colours (ii) good surface finished parts with transparent materials. Polyjet 3DP process creates parts by jetting multiple photopolymer materials as modelled in CAD in ultra-thin layers (approx. 16μ) onto a part build tray layer by layer until the part is completed. Each multi-material photopolymer layer is cured by UV light immediately after it is jetted, producing fully cured models. From literature it was observed that Polyjet 3DP process has been used to fabricate assembled part with two different materials for different parts or region of the assembly. But in this work based upon CAD modelling build strategy which is described under Section 2.1, AM part were directionally reinforced within a layer.

Polyjet 3DP can process wide range of materials ranging from opaque to transparent, rigid plastic to rubber-like materials [22]. Among these range of materials, the mechanical properties of the AM structure fabricated through polyjet 3DP can be altered by selecting suitable combination of materials. This new combination will provide new values of flexural strength, tensile strength and impact strength. Table 1. represents the mechanical properties of materials considered for fabrication of reinforced AM structure. Darus white is "polypropylene like" material with a high percentage of elongation (40–50%) at break. Darus white is generally used in fabrication of functional parts, living hinges and over moulds. In some of the above mentioned applications improvement in stiffness is necessary without compromising the flexibility. To achieve above mentioned functionality high strength "ABS like" vero black and flexible "polypropylene like" darus white material was assigned to reinforcement and matrix respectively.

2.3. Tensile testing

Tensile tests were conducted over AM structure to determine their elastic modulus. Pure reinforcement and matrix AM structure, reinforced AM structure with reinforcement oriented at three different directions were tested using Instron tensile testing machine in accordance to ASTM: D638 standard as shown in Fig. 2a. Constituent and composition of material for unreinforced and reinforced AM structure were summarized in Table 2. A set