Understanding the Anisotropic Characteristics of 3D Printed Parts

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Abstract

Additive manufacturing (AM), also known as 3D printing, is a fabrication method that creates parts layer-by-layer based on the shape information provided as a CAD file. Currently, there are numerous 3D printing technologies and compatible 3D printing materials available to create products for various purposes ranging from prototyping to end-use. Additive manufacturing technology is particularly important for Generative Design (GD) applications because any 3D CAD model created using a CAD software program or any product design recommended by a GD software program can be 3D printed regardless of how complex the shape is. However, current GD software programs do not consider the printing orientation of the parts, which directly affects the printed part's mechanical characteristics due to the anisotropic behavior of the 3D printed components. The aim of this study is to identify the mechanical characteristics of selected 3D printing materials for the selected 3D printing technologies through mechanical testing of 3D printed parts. The results of this study will be used to identify the issues related to the anisotropic characteristics of the materials. It will help design engineers and researchers to be able to employ appropriate 3D printing technologies for the materials selected and be able to determine a better product shape and printing orientation among the designs recommended by the GD software program. This research is a work-in-progress. In the current state, mechanical characteristics of Stereolithography (SLA) and Micro-Fiber Reinforced (MFR) 3D printed parts are evaluated through tensile tensing. When completed, Fused Deposition Modeling and Continuous Fiber Reinforced 3D printing technologies will be studied, as well.

Introduction

Engineers use various scientific and engineering tools and methods to define, design, and analyze their solutions or products. One of the latest engineering design tools that is capable of generating solutions to design problems is "Generative Design" (GD) technology. Generative Design software is an advanced engineering design simulation that can produce multiple design alternatives/solutions based on a set of functions, specifications, and constraints defined by the design engineers. The major difference between GD and the other engineering tools, such as Finite Element Analysis (FEA), is that GD optimizes the shape of the design solution based on the manufacturing process selected by the design engineer. So, the design and shape solution recommended by GD for five-axis machining will be different from a solution developed for the casting process. In order to use the power of GD to the full extent, one specific area that requires more investigation is additive manufacturing.

Additive manufacturing (AM) is a manufacturing technology that produces parts and assemblies
layer-by-layer according to the digital information provided by Computer-Aided Design (CAD) software\(^1\). When the technology first came out, the most significant hurdles were the extremely low production speed, poor surface quality, and limited available materials\(^2\). Today, complex parts and assemblies can be easily produced from industrial-grade polymers, ceramics, metals, and composites with desirable precision and mechanical characteristics at an acceptable speed\(^3\). With the help of technological advancements in additive manufacturing technologies, 3D printing has become a mainstream manufacturing process that can be feasibly used in numerous industries such as automotive, aerospace, medical, and dental\(^4\). The widespread use of 3D printing in such various and critical applications has made it necessary to conduct research on the dependability of this technology and the quality of the finished parts and materials used.

Creating a part "layer-by-layer" introduces an undesirable anisotropic characteristic to the finished product\(^5\). The engineer's choice of printing orientation on the build plate directly affects the printed part's mechanical characteristics due to the anisotropic behavior of the 3D printed components. The aim of this study is to identify the mechanical characteristics of 3D printing materials through mechanical testing of 3D printed parts.

**Methodology**

In order to analyze the effects of printing orientation on the mechanical characteristics of the printed parts, type IV tensile test coupons are printed according to ASTM D638-14. Seven printing orientations are determined, as seen in Figure 1.

![Figure 1. Printing Orientations of Test Specimens.](image)

In orientation 1, the part is printed on its largest flat surface. In orientations 6, 7, and 2, part is rotated around the long edge for 30°, 60°, and 90°, respectively. In orientations 4, 5, and 3, part is rotated around the short edge for 30°, 60°, and 90°, respectively. Five specimens were printed for each orientation using SLA and MFR technologies. SLA technology prints parts from a photosensitive liquid resin by curing the resin layer-by-layer with a laser. In FMR technology, a
microfiber reinforced nylon filament is heated and extruded on a build plate layer-by-layer. A Formlabs Form 2 3D printer with clear resin (RS-F2-GPCL-04) was used for the SLA technology. Markforged Mark 2 3D printer with Onyx (micro carbon fiber-filled nylon) material was used for the MFR technology. After the parts are printed and post-processed, tensile testing is performed with ADMET tensile tester, which has a 1,000 lb load capacity. Elongation is measured with an Epsilon axial extensometer (Model 3452) with a 25mm gauge length.

Results

SLA - Clear resin
The stress-strain curves for SLA parts show that the "clear resin" material has ductile characteristics with a significant plastic deformation zone (Figure 2).

![Stress–Strain Curve of an SLA 3D Printed Test Specimen in Orientation 1.](image)

Figure 2. Stress – Strain Curve of an SLA 3D Printed Test Specimen in Orientation 1.

Average Ultimate Tensile Strength analysis revealed that the highest strength is achieved when the part is in the flat orientation or 90° rotated from the long and short edges (Figure 3). This is consistent with the average deformation at the failure point (Figure 3). The part orientations with higher strength present less deformation at the failure point.

![Average Ultimate Tensile Strength and Average Maximum Elongation](image)

Figure 3. Average Ultimate Tensile Strength and Average Maximum Elongation

The SLA parts in 90° orientation are stronger and more brittle than all other orientations because when the laser is scanning to cure a new layer, previously cured layers are also exposed to the laser. The position of the laser shifts after each scan in other orientations, so the previously cured layers...
are not exposed to the laser as much, as seen in Figure 4.

Figure 4. Laser curing a layer in 90° orientation on the left vs tilted orientation on the right.

**MFR – Micro-Fiber Reinforced Nylon**

The stress-strain curves show that when the part is printed in the flat orientation, it shows tough and ductile characteristics (Figure 5). However, the specimen behaves like a brittle part without significant deformation when the part is printed in a rotated orientation around the short edge. The average ultimate tensile strength of FDM parts shows that when the parts are printed flat or rotated around their long edge, the strength increases. However, the strength is reduced significantly when the parts are oriented at 30°, 60° or 90° around the short edge (Figure 6).

Figure 5. Stress – Strain Curve of an FDM Printed Test Specimen in Orientation 1 (on the left side) and Orientation 5 (on the right side).

Figure 6. Average Ultimate Tensile Strength and Average Maximum Elongation

As seen in Figure 7, when the parts are oriented at 30°, 60° or 90° around the short edge, the part is delaminated. In other orientations, ductile fracture is observed.
Summary and Conclusions

From the tensile testing of printed parts, it is evident that the print orientation significantly affects the tensile strength of 3D printed parts with SLA and FDM technologies. Since this is a work-in-progress, more research will be performed to understand why and how printing orientation affects printed parts' mechanical performance depending on the selected printing technology and material.

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References


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