Advances in Technology Innovation, vol. 3, no. 4, 2018, pp. 179 - 184

Evaluation of Infill Effect on Mechanical Properties of Consumer 3D Printing Materials

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Received 20 July 2017; received in revised form 04 December 2017; accepted 05 December 2017

Abstract

During the additive manufacturing "boom" of the last decade, consumer level 3D printers have kept pace with commercial/industrial printers, both in numbers and features. However, in material characterization data, the access to date for the consumer has significantly lagged behind. Consumer level 3D printers provide a significant asset to entrepreneurs, small businesses, universities, college students, and hobbyists due to the low initial capital cost and relatively low operational costs. Commercial grade 3D printers and the associated filaments sold for their use typically have well documented material properties and print parameters. Consumer 3D printers, however, typically have limited or no access to mechanical test data for their materials. This paper describes the work of the authors to fill the existing knowledge gap in the mechanical properties of consumer level 3D printer filament. ASTM Tensile (D638) tests were performed on samples produced by two commercially available 3D printers. The materials tested include PLA, ABS, PETG, various nylons, Polycarbonate/ABS, and ASA filaments. Samples were printed with infill percentages ranging from 15% to 100% to test for tensile properties.

Keywords: additive manufacturing, polymers, 3D printing, tensile testing, thermoplastics

1. Introduction

Additive manufacturing, often referred to as 3D printing, gives companies and individuals the ability to rapidly design, test, and improve concepts, as well as the ability to mass-produce components. Commercial machines, while expensive to own and operate, produce consistent and reliable printed components due to the mechanical testing and process optimization performed along with the development of the printer. Thus far, the testing and process optimization for consumer-level machines has lagged. Since some consumer 3D printing is employed by hobbyists, the strength of available printing materials has been considered irrelevant. However, for those producing load-bearing components with consumer-level 3D printers, the strength of printing-compatible materials are important.

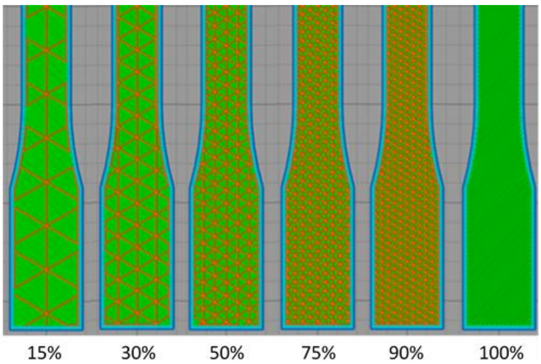

Fig. 1 Infill comparison for printed components

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ASTM (American Society of Testing and Materials) Standard D638, Standard Test Method for Tensile Properties of Plastics, was used as a guide for the testing procedure [1]. For this work, the infill percentages shown in Fig. 1 were tested. The 15%-90% samples were a triangular infill, with infill lines at 0°, +60°, and -60° relative to the principle axis of the tensile specimen. Due to the nature of the slicing software, the 100% sample had to be printed with solid layers in a ±45° orientation, relative to the principle axis of the specimen. Although each material is printed at different temperatures with different travel speeds according to the needs of the material, the final geometry allows for direct comparison between materials.

2. Materials Tested

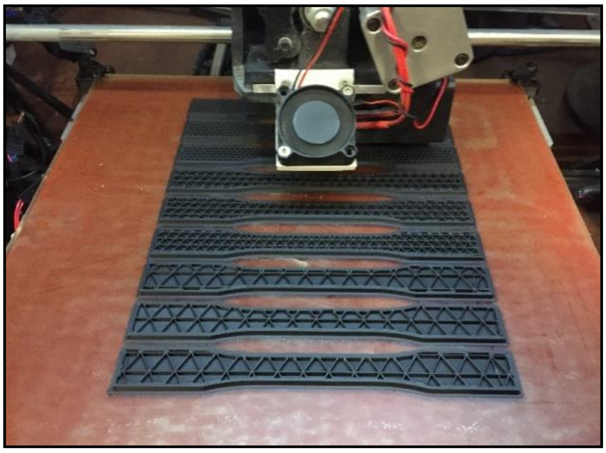
In total, seven materials were tested for a total of three companies. Polylactic Acid (PLA) is a common material for 3D Printing [2]. It is relatively easy to print, but is somewhat brittle and has a low service temperature. Acrylonitrile Butadiene Styrene (ABS), often used for injection molded components, is likely the most common thermoplastic in use today [2]. ABS can be more difficult to print due to layer bonding and warping issues, but has improved mechanical properties over the PLA. Polyethylene Terephthalate Glycol (PETG), a thermoplastic co-polyester, is quickly becoming a more common material for 3D Printing [3]. Acrylonitrile Styrene Acrylate (ASA) is a UV-stable thermoplastic, often used in the marine, auto, and RV industries due to its weathering resistance [4]. ASA is similar to ABS in terms of mechanical properties and printing parameters. Polycarbonate/ABS (PC/ABS) is a blended thermoplastic, designed for high-heat applications [5]. PC/ABS also has a high tendency to warp, though an enclosed build volume reduces the tendency to warp. PETG produces parts with little to no warping, but can have a poor surface finish if improper printer settings are used. PLA, ABS, and PETG were all purchased from the company MakerGeeks. The ASA and PC/ABS were purchased from another company. The nylon materials tested were all produced by the company taulman3D. Nylon materials are known for their strength, chemical, and thermal resistance. Nylon 645 is a specially designed nylon 6/9, optimized for improved tensile strength and improved optical clarity [6]. Nylon 910 is a special form of nylon developed by taulman3D expressly for the purpose of 3D printing. It is extremely tough, strong, and resistant to high temperatures [6]. Table 1 shows a summary of the published material properties for the materials tested in this work. σY is the yied stress, or the stress at which the material begins to rupture, leading to failure.

Table 1 Approximate material properties of printed materials, taken from various sources

Material	Density [g/cm3]	σY [MPa]	Modulus [GPa]	Failure Strain [%]
PLA [12]	1.29	44.8	3.8	23.1
ABS [13]	1.07	43.3	2.3	24.8
ASA [4]	1.08	44.6	2.3	34.1
PC/ABS [5]	1.17	56.0	2.7	63.3
PETG [3]	1.27	65	3.0	109.0
Nylon 6/6 [9]	1.14	75	2.8	50

3. Specimen Production

The specimens tested in this work were produced using two commercially available printers, shown in Fig. 2. Table 2 shows a summary of the printing parameters used for each material and indicates which machine printed each sample. The PLA, ABS, PETG, and Nylon materials were printed from nominal 2.85mm printer filament, while the ASA and PC/ABS were printed from nominal 1.75mm printer filament. The dimensions of the samples were taken from the Type 1 sample defined by the ASTM standard [1]. This specimen type was chosen since it is large enough for the printing infill to become a predominate component of the specimen strength. In Fig. 2, the left image is of a commercially available, consumer-grade 3D printer, while the right image is of a printer constructed by the author from a kit of parts. Simplify3D was used as the slicing software and all the printer Gcode files were produced through it. Samples were produced in groups of three according to infill percentage, labeled, and organized by sample type. Samples with apparent flaws in the test section or radius, as well as samples that were warped, were reprinted. In order to improve print quality, all materials were dried for at least 24 hours in a desiccant-filled box heated to 45℃. Filament drying is optional for some materials, but ABS, ASA, PETG, nylon, and PC/ABS materials are hydroscopic and must be dried prior to printing [7]. Some materials with a high possibility of warping, such as the nylons or ABS, were printed with a brim; a single-layer feature added by the slicing software to increase the bed contact area, thereby increasing adhesion and reducing warping. Aside from the printing parameters mentioned in Table 2, all samples were printed with three top/bottom layers, three perimeters, and a triangular infill pattern. The 100% infill samples were printed solid by forcing the slicing software to make top/bottom layers through the whole thickness of the part. The print cooling fan was used for PLA, ABS, and PETG in order to improve the surface finish. Previous work by Lanzotti indicates that the number of external perimeters has a much larger effect on tensile strength than layer thickness, so layer thickness was chosen according to material-specific best practice [8].



(a) ABS 15, 30, and 50% specimens mid-print on Printer 1

(b) PC/ABS 90% specimens min-print on Printer 2

Fig. 2 Print parameters for all materials

Table 2 Print parameters for all materials

Material	Printer	Temperatures [℃] (Hot End/ Bed)	Layer Height [mm]	Print Speed [mm/s]
PLA	1	215/70	0.21	45
ABS	1	250/110	0.22	40
PETG	1	245/70	0.25	45
Nylon 910	1	235/100	0.25	30
Nylon 645	1	235/110	0.25	20
ASA	2	245/110	0.20	35
PC/ABS	2	285/115	0.25	30

4. Test Method

Fig. 3 Specimen loaded in tensile testing machine, prepared for test

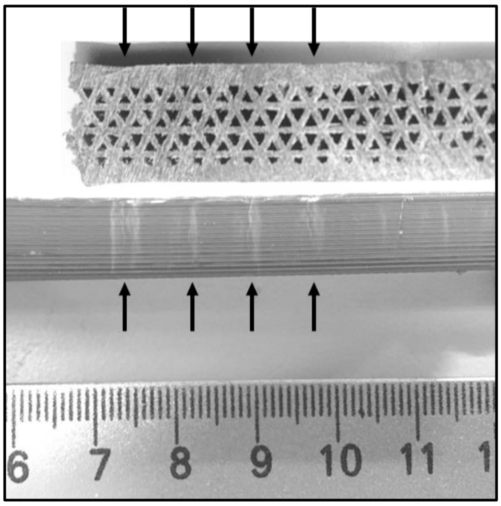


Fig. 4 Crazing marks visible on outside of ABS 50% infill sample

After printing, samples were removed from the print bed, post-processed to remove the brim (if present), labeled according to material, infill percentage, and specimen number, measured with digital calipers, and then tested. Testing was performed using a MTI 5K bench-top universal testing system fitted with serrated-jaw tensile grips and an Epsilon strain extensometer rated for 10% strain. Samples were loaded into the jaws, checked for vertical alignment, and then tested at a crosshead travel speed of 50 mm/min, as specified by the ASTM Standard for rigid polymers [1]. Fig. 3 shows an example of a specimen loaded in the tensile testing machine, prior to testing. After specimen failure, the extensometer was removed from the specimen and the specimen removed from the tensile jaws. Failed specimens were retained for photography and analysis. Due to supply limitations, only three samples each material was tested unless the sample needed to be retested due to a test failure.

5. Results

Fig. 7 shows a summary of these results, comparing average tensile data from all materials tested**.** As expected, the tensile yield strength of the samples was directly affected by infill percentage. At 15% infill, all seven materials had a yield stress less than 25 MPa. The PC/ABS was the strongest at 15% infill, while ASA, ABS, and Nylon 910 tied for the lowest yield strength at 15% infill. As the infill percentage increased, the range of yield strengths also increased. At 30% infill PLA had a yield strength of 30.1 MPa, while the Nylon 910 had a yield strength of 13.1 MPa. The 50% infill samples had a tighter range of tensile strengths, varying from 30MPa (PC/ABS) to 15.6 MPa (Nylon 910). Above 50% infill, the yield strengths began to increase significantly. At 75% infill, the PETG had an average tensile yield strength of 36.1 MPa while the ASA had an average tensile yield strength of 19.1 MPa. Finally, at 100% infill, the Nylon 910 had an average yield stress of 69.9 MPa, making it the strongest material tested. PLA, which was the weakest material at 100% infill, had an average yield stress of 32.98 MPa. On an individual-material level, Nylon 910 was the most affected by infill percentage; 12.7 MPa at 15% infill to 69.9 MPa at 100% infill, a difference of 57.2 MPa. PLA, while weaker overall, varied considerably less than the Nylon 910; 18.4 MPa at 15% infill to 32.9 MPa at 100% infill, a difference of 14.5 MPa. At 30% infill, the PLA had the highest tensile strength of 30.1 MPa, a value higher than the 50% and 75% infill tensile strengths for the same material. PETG varied from 16.4 MPa at 15% infill to 51.8 MPa at 100% infill, a variance of 35.4 MPa.

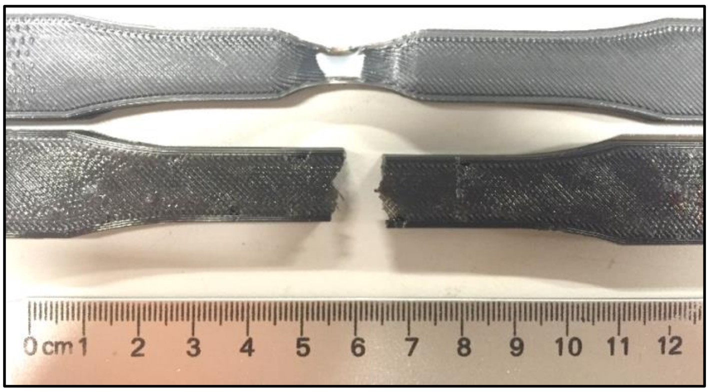


Fig. 5 Comparison of ductile (top) and brittle (bottom) failure modes for two PETG specimens. The top specimen is 100% infill while the bottom sample is 30% infill

The modulus of elasticity is also dependent on infill percentage. As the infill percentage increases, so does the modulus. This effect can be seen in Fig. 6, which show a comparison of different infill percentages within the PETG material. The slope of the elastic region of the data line is the modulus of elasticity, which increases as the infill percentage increases. For the PETG, the modulus increased from 0.69 GPa to 1.85 GPa as the infill percentage increased from 15% to 100%. Fig. 5 shows how the 30% PETG sample failed with almost no deformation, while the 100% sample exhibited necking prior to failure. Nylon 910 varied from 0.34 GPa to 2.44 GPa as the infill increases from 15% to 100%. The remaining materials also indicate modulus dependence on infill percentage.

In some materials, the infill percentage affected the failure mode of the specimens. For example, in Fig. 5, the PETG 100% infill specimen failed in a ductile manner, as indicated by the severe necking in the center of the reduced section. The bottom specimen in Fig. 5, which was a PETG 30% infill specimen, failed in a more brittle manner. These failure modes are supported by the data from PETG tests shown in Fig. 6; the curve for the 30% specimen fails without much plasticity (failure at 3.22% strain) while the 100% curve indicates plastic deformation (failure at 11.3% strain). The Nylon 910 failed in a similar manner, though all of the 910 samples had some degree of plasticity prior to failure. All infill percentages of the PLA samples failed in a brittle manner, with no visible necking or deformation prior to failure. The ABS samples showed evidence of crazing, a change in color due to mechanical deformation, prior to failure [9]. Fig. 4 shows an example of the crazing on an ABS sample, as well as a cross section of the failed component. Of particular interest in Fig. 4 is the alignment of the crazing marks with the infill lines. The top of Fig. 4 shows a cross section of the same sample shown in the center of Fig. 4. Many of the specimen failures occurred along an infill line, indicating that the infill pattern may cause a stress concentration.

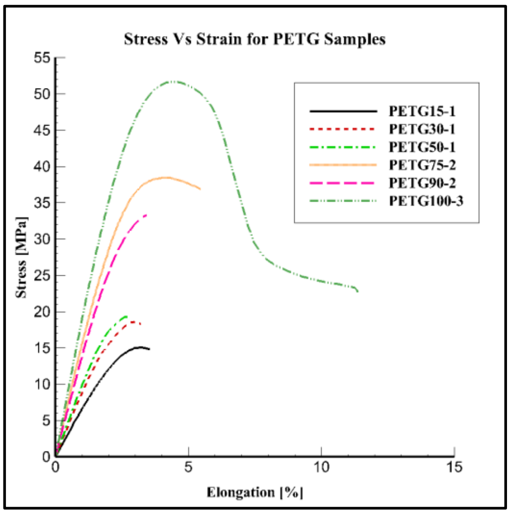


Fig. 6 Comparison of tensile data for PETG samples. Legend format: PETG[% Infill]-[Sample Number]

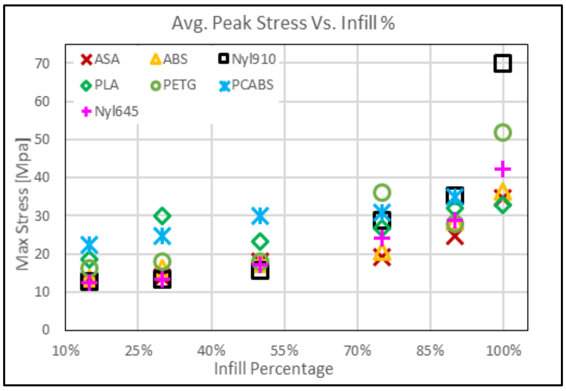


Fig. 7 Average tensile strengths for all materials tested at a variety of infill percentages

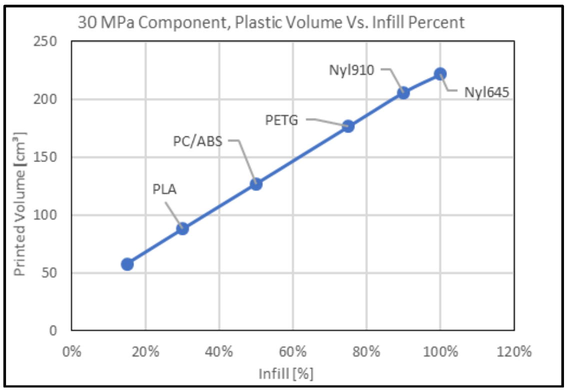


Fig. 8 Comparison of required infill percentages for same component strength

While the 100% infill specimens are consistently the strongest, solid components take more time and material to produce. There exists a "sweet-spot," a point at which material and time costs are minimized while component strength is maximized. For evaluation of this sweet-spot, consider a cube with 60mm sides (216 cm^3 volume), that needs to have a tensile strength of at least 30 MPa. If any of the materials tested in this work were available, each would require a different infill percentage to achieve this strength. Since the volume of polymer filament required directly affects the cost of printed components, required polymer volume is an important design consideration. Fig. 8 represents this concept graphically, showing that in order to reach the desired tensile strength, different infill percentages need to be used depending on the material used. Not represented in Fig. 8, but still of importance to anyone designing a printed component, are the ultimate strain of the plastic, chemical resistance, and thermal-mechanical properties. Evaluating the effect of infill on these mechanical properties is beyond the scope of this work.

6. Conclusions

The data presented from this research provides a design basis for the designer seeking to create a component with a specific loading requirement**.** This project tested seven materials from three manufacturers of polymer filament. Two consumer-grade, open-sourced 3D printers were used to fabricate the tensile specimens. At 100% infill, Nylon 910 had the highest tensile strength at 69 MPa, while PLA was the weakest at 33 MPa. As the infill percentage decreased, the range of tensile strengths for all materials was more tightly grouped, indicating that infill percentage has a significant impact on tensile strength. Infill percentage was also found to affect modulus, elongation, and failure mode.

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