On the Mechanical Properties of 3D Printed Parts for Design Optimization

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Work in Progress: On the Mechanical Properties of 3D Printed Parts for Design Optimization

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***Abstract* - This paper reports on a work-in-progress student funded research program to measure the mechanical properties of parts created through additive manufacturing or 3D printing. It is difficult to predict the final performance of 3D printed parts due to the large number of technologies, materials, and print parameters which result in a layered, composite structure that differs considerably from a "solid" part. Our research focus includes print parameters such as infill density and the number of exterior shells. We print parts in our 3D print lab with PLA filament and test them in our materials lab in accordance with ASTM standards for tension and compression testing. An analysis of the stress-strain diagram gives the elastic modulus of the part in the elastic region as well as the yield and ultimate stresses. A goal of this research is to understand the correlation between print parameters and the strength to weight ratio of a part to determine the optimal print parameters when designing parts. Additive manufacturing is introduced to freshmen mechanical engineers through experiential learning projects in 2D/3D Modeling and Intro to Engineering Design courses. The knowledge of 3D printing the students acquire in their first year benefits the students for their remaining college years as well as their futures in industry and academia. A further goal of this research program is to enable funded research opportunities at the first year level which is critical to the development of successful student research methodologies and achieving scholarly publications.**

Index Terms – additive manufacturing, 3D printing, material testing, student research.

INTRODUCTION

The benefits of additive manufacturing (A.M.) and the impact on traditional manufacturing industries have been well established [1]. In fact, A.M. has been called the next industrial revolution [2]. However, due to the complex nature of the processes, with a large variety of inputs to the system, including the various technologies, the associated material properties, and the user selected print parameters, it is difficult to predict the performance of parts fabricated with these new methods. Due to the user defined print parameters defined during slicing, the printed part differs, often dramatically, from the originally designed part. Notably, the parts are often partially hollow to save on time and materials during the printing process. In this work we selected Fused Deposition Modeling (FDM) and polylactic acid (PLA) plastic filament as the technology and material and focused on the statistical repeatability of the performance of the parts. This paper reports on a work in progress research program which is performed with undergraduate students who aid in design, printing, testing, and analysis of the parts.

METHOD

Prior research work has identified several user selected print parameters that affect the performance of a part such as layer height, infill pattern, print orientation, and exterior shells. Often large numbers of parameters are included in the studies, but due to the large number of combinations, and the time consuming task of printing parts for testing, only a subset is actually printed, and statistical methods are used to infer the impact of individual parameters [3]-[6]. In previous research we focused on two parameters, infill density and exterior shells, with five allowed values for each, yielding a matrix of 25 combinations, all of which were printed and tested. In this current research we are studying the variation in performance of multiple copies of the same part, printed with a single set of parameters on the same machine. To this end, we printed ten copies of a one inch cube for compression testing and five copies of a six inch standard dog-bone for tension testing which are shown in Figure 1.

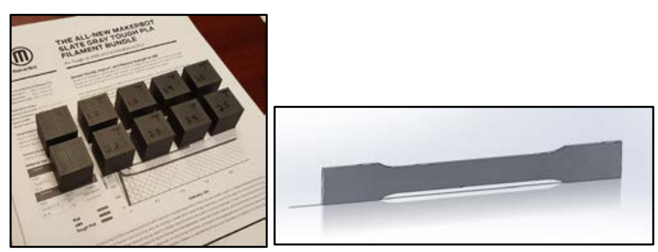

FIGURE 1
COMPRESSION AND TENSION TESTING SAMPLES.

Compression tests were performed in accordance with ASTM Testing Standard D695-15 [7] on the ten cube test specimens. The CAD models were designed in SolidWorks, converted to STL file format, sliced with the MakerBot Print software, and printed on our MakerBot Z18 machine. Several print parameters are given in the following table, with the most relevant being the layer height, infill density, and number of shells.

TABLE 1
PRINT PARAMETERS FOR COMPRESSION SPECIMENS

Parameter	Value
Layer height	.3 mm
Infill pattern	linear
Infill density	10%
Exterior shells	2
Raster angle	0 deg
Extruder temperature	215 °C

To determine the elastic modulus of the parts, they were tested in our Materials Testing Lab on two Instron 5566 machines, one outfitted for compression and the other for tension. The results of the testing yield a stress-strain diagram from which one can measure the change in length of the sample under axial loading. The initial deformation occurs in the elastic region (Fig 2), where the material behaves as a spring and will return to its original length when the load is removed. Continued loading causes permanent deformation in the plastic region, beyond which the part will eventually fail. The slope of the line in the linear region yields the Young's Modulus of the material which is measure of the toughness of the object [9].

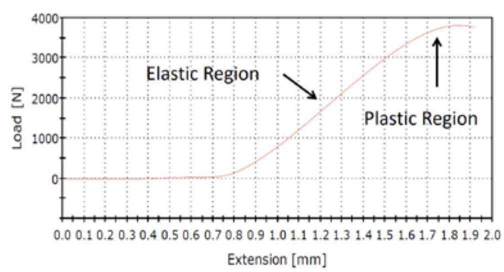

FIGURE 2
STRESS – STRAIN DIAGRAM.

Tension tests were performed in accordance with ASTM Testing Standard D638-14 [8] on the dog-bone test specimens. The CAD models were designed in SolidWorks, converted to STL file format, sliced with the MakerBot Print software, and printed on our MakerBot Z18 machine with the following parameters:

TABLE 2
PRINT PARAMETERS FOR TENSION SPECIMENS

Parameter	Value
Layer height	.3 mm
Infill pattern	linear
Infill density	100%
Exterior shells	1
Raster angle	0 deg
Extruder temperature	215 °C
Part orientation	flat

RESULTS

Prior to testing, the cube's masses were measured on an analytic force balance and determined to have an average mass of 5.255 grams with a population standard deviation of $\sigma = .0107$ grams. For each specimen the elastic region of the stress-strain data was fit with a linear trendline over the applied force range 2000-3000 N. The R-values of the best fit lines are .9997 or greater, giving confidence to the linear trendline. A typical result from the compression tests is shown in Fig. 3, where the modulus of elasticity of the test specimen is found from the slope of the linear best fit line, in this case 183.62 MPa. With student aid, all ten specimens were put under compressive testing.

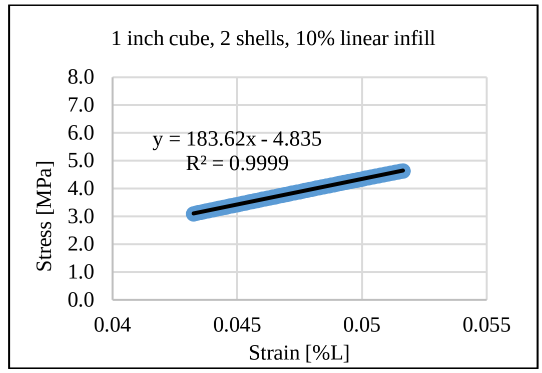

FIGURE 3
STRESS – STRAIN DATA, COMPRESSION TESTING.

The results of the ten compression tests are shown in Table 3. A close range of modulus of elasticity was found with an average value of 177.53 MPa and a population standard deviation of $\sigma = 5.12$, which dividing the mean by the standard deviation yields a coefficient of variation of 2.88%.

TABLE 3
MASS AND ELASTIC MODULUS OF COMPRESSION SPECIMENS

Part #	Mass (g)	Modulus (MPa)
1.1	5.260	183.62
1.2	5.234	178.44
1.3	5.257	177.19
1.4	5.251	177.46
1.5	5.241	168.86
2.1	5.267	181.86
2.2	5.254	185.62
2.3	5.268	176.54
2.4	5.259	175.96
2.5	5.260	169.71

Next, the five dog-bone specimens were tested at the tension station. In this case, axial loading leads to an elongation of the part, but the stress-strain diagram exhibits behavior similar to compression. Because the geometry of the dog-bone is anisotropic, the print orientation must be specified. In all cases the dog bones were printed flat, with the largest surface area side on the build plate. Again, prior to testing, the parts were weighed on a force balance. Their masses, like the cubes, showed a very close range of values, with an average of 4.781 grams and standard deviation of $\sigma =$ .015 grams (Table 4).

For each specimen the elastic region of the graph was fit with a linear trendline over the applied force range 200-400 N. The R-values for these trendlines were all greater than

.9999 giving strong confidence to the fit. A typical graph from the tension tests with the linear trendline is shown in Fig. 4. The stress-strain diagrams were generated by taking the raw data from the Instron (Force and ΔL) and converting to pressure and % length by using the area and height of the specimens which were measured for each specimen.

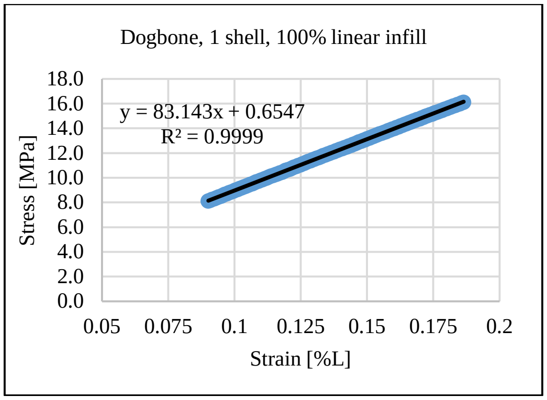

FIGURE 4
STRESS – STRAIN DATA, TENSION TESTING.

The results of the five tension tests are shown in Table 4. A range of elastic modulus was found with an average value of 83.020 MPa and a population standard deviation, $\sigma = 1.57$. Dividing the mean by the standard deviation yields a coefficient of variation of only 1.90% for the samples in the tension tests.

TABLE 4
MASS AND ELASTIC MODULUS OF TENSION SPECIMENS

Part #	Mass (g)	Modulus (MPa)
3.1	4.790	83.143
3.2	4.801	84.083
3.3	4.775	80.187
3.4	4.781	84.810
3.5	4.757	82.877

STUDENT EXPERIENCE

As additive manufacturing technologies become more and more prevalent in industry, it is increasingly important that new engineers are knowledgeable of these processes. In fact, there are many start-up A.M. companies in this region, and several of their CEO's have expressed to me their need for engineers who are adept at working in this new sector. To this end, I was an early adopter of 3D printing at my University and have several avenues of introducing students to these emerging technologies.

The first step was into introduce A.M. to Mechanical Engineering students in a freshman level solid modeling (CAD) course. Through new curriculum, an experiential learning project, and hands on access to the print lab, students are exposed to and gain experience in 3D printing. In my first-year Engineering Design course students are then encouraged to use A.M. methods to rapid prototype their designs. Next, I started a 3D Print Club where students can regularly meet and engage in a variety of activities, including educational events, tours of local companies, and get access to the print lab. Successful students who have demonstrated a desire and aptitude for 3D printing are then eligible to work on applied research projects (Fig. 5).

Our university has funding for student research (PSRA grant) with a faculty member which requires a formal proposal submission. The past president of the Print Club won this award and was able to perform funded undergraduate research on 3D printed parts. This work led to two presentations at undergraduate research conferences.

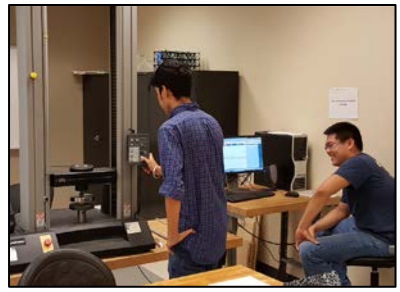

FIGURE 5
STUDENTS PREPARING FOR COMPRESSION TESTING.

The knowledge and hands on experience of 3D printing the students acquire in their first year of engineering benefits the students for their remaining college years as well as their futures in industry and academia. A further goal of this research program is to expose students to funded research opportunities at the first year level which is critical to the development of successful student research methodologies and in achieving scholarly publications.

FUTURE WORK

The long term goal of this work is to develop computational models of additive manufacturing process and to apply numerical optimization techniques to aid in the design and performance of parts created with additive manufacturing technologies. The first step is to develop empirical models that relate print parameters to measureable quantities. These models will be validated with these experimental efforts.

ACKNOWLEDGMENT

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