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Acquiring Testing of Materials Experience Through 3D Printing (WIP)

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Abstract

In a multidisciplinary Engineering Technology (ET) program with 5 different concentrations, it is not possible to cover the detailed theory and applications of all high-level classes. For this reason, many educational projects are aimed to give students the opportunity to acquire this high-level knowledge through hands-on practice. At the end of these projects, students conclude their experience and prepare a student manual that, later on, guides other groups in getting the same knowledge through hands-on experience. This initiative is applied through some senior design projects as well as through support from agencies such as the Louisiana NASA space grant (LaSPACE). In this paper, an investigation of the effect of 3D printing parameters on the mechanical properties was performed by a senior design student funded by LaSPACE. The scope of the project includes the studying of some printing parameters such as the printing orientation and infill density on the mechanical properties of the commonly used polylactide (PLA), learning experience included following the ASTM standards for tensile and Charpy tests for 3D printed materials, learning how to set up a bench-top vertical testing stand, setup extensometer, and the basics of data acquisition from a load cell and an extensometer using two different software. Along with these learning outcomes, students could analyze the resulting data and compare results to some commercially available data. Besides its undergraduate research component, this project is aimed to expose students to more testing of materials techniques to supplement the knowledge acquired during the course of study in the Engineering Technology program. The acquired experience will be presented with partial results of the project in this work in process.

Objectives

The main objective was to educate the Engineering Technology (ET) undergraduate students about testing of materials methodology, standards, codes, and to perform relevant research. A MakerBot Replicator+ 3D printer was used, with both the regular and tough extrusion heads, to print tensile and Charpy specimens of PLA and tough PLA materials. A bench-top vertical testing stand (Universal Testing Machine PCE-MTS500), a Tinius Olsen Impact Tester IT542, an extensometer, and data acquisitions connected to the load cell and the extensometer, and two different data acquisition software were utilized in the experiments. Figure 1 shows the equipment used in the project.

Problem Statement

The advance in 3D printing contributes to modern industry as well as space exploration. 3D printing is a form of Additive Manufacturing that allows manufacturing of parts in an efficient and economical way compared to subtractive manufacturing and other conventional production methods. The properties, performance, and reliability of the 3D printed products vary based on several printing configurations. In the past decade, investigations of mechanical properties of 3D printed materials have been done but were limited to some aspects and configurations of the printing process. In this project, an investigation of the effect of 3D printing parameters on the mechanical properties was performed. The scope of the project includes the studying of printing parameters such as printing orientation, infill density, and infill pattern on the mechanical properties of the commonly used polylactide (PLA) and its Tough version.

Figure 1 PCE Vertical Test Stand (left) and Tinus Olsen Charpy Machine (right).

Methods

Two ET senior design students were assigned to work on this project. The senior design classes are capstone courses where students utilize their cumulative engineering knowledge towards a real-life project through research and experimentation. They come in a sequence of two 3-credit classes in 2 competitive semesters (Senior Design I & Senior Design II). ASTM standards were first researched to determine specimen size and dimensions for the tests performed. Tensile and Charpy impact tests were performed following the ASTM standards for tensile and Charpy tests for 3D printed materials. A MakerBot Replicator+ 3D printer was used with both the regular and tough extrusion heads to print the test specimens for both tests. To set a code for the printed test specimens, the direction of the longer dimension of the 3D printer's build plate was set to be the X direction while the shorter dimension was set to be the Y direction. The direction normal to the build plate was set to be the Z direction, Figure 2.

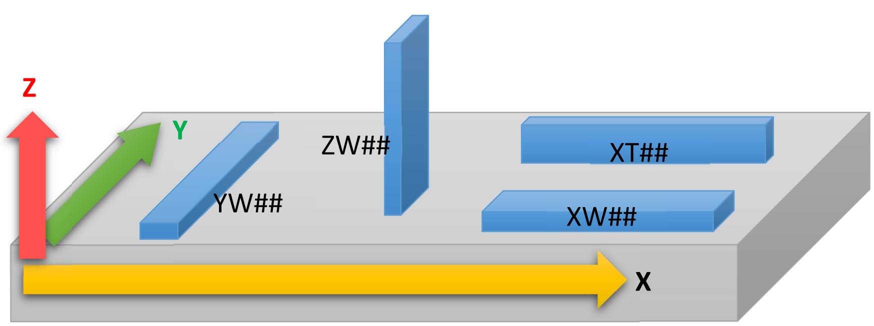
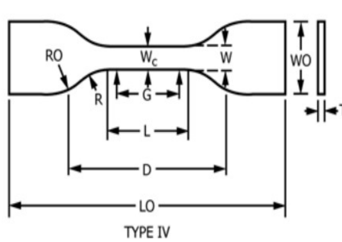


Figure 2. 3D Printer build plate, printing orientation, and specimen coding

All unique orientations were defined and coded as follows: The first letter in the code is the direction of the length of the specimen with respect to the build plate (X, Y, or Z). Based on which side of the specimen is laid on the build plate (length, width, thickness), the second letter takes one of the letters W, T, or L. The second letter is the dimension (L, W, or T) in the direction of Y (or in direction of X if the first letter is Y). The 2-digit number, at the end of the code, represents the percentage infill. The number after the hyphen represents the specimen number among the same configuration. So, the code YW95-4 represents the fourth specimen printed with its length directed along the Y axis and its width directed along the X axis with 95% infill. Also, the code ZT20-3 represents the third specimen printed with its length directed along the Z axis and its thickness directed along the X axis with 20% infill. That was the initial code used for the early stages of testing until the filament material and the number of shells were added as the 4th and 5th elements in the code. The number of shells were added after the first 2 letters followed by either R, for Regular PLA, or T, for The Tough filament. This was the code that was decided to be used for the remaining specimens and future experiments. So, a code XT3T75-3 represents the third tough specimen printed with its length along the X axis with 75% infill.

ASTM D638 is the test standard for tensile testing of PLA plastic. The ASTM D638 standard, for testing the tensile strength of plastics and other resin materials, specifies 5 acceptable designs for the dogbone-shaped rectangle specimen (Type I through Type V) with their dimensions. A specimen of each type was 3D printed and analyzed to determine which type fits best in the vertical test stand used. Ultimately, type IV was chosen to be the specimen type for tensile testing due to its size, Figure 3, as it is small enough to have quick prints but also big enough to have valid test results. The ASTM standard chosen for this toughness specimen was ASTM A370 because that was the required standard for the Charpy machine on campus. The dimensions for the A370 specimen can be seen in Figure 4. Students were trained to use the 3D printer, the vertical test stand, and the Charpy impact tester. A few test prints were completed to make sure the printers were running correctly. Then an Excel file was created to plan out the prints for the tensile specimens. Part of the excel file can be seen on Table 1. Each specimen has a different orientation, material, shell, and face. These were the independent variables chosen for the test specimens. As these variables change, the test results will also change, and a conclusion from that data can be made.



	Type IV[B]
W—Width of narrow section[E,F]	6 (0.25)
L—Length of narrow section	33 (1.30)
WO—Width overall, min[G]	19 (0.75)
WO—Width overall, min[G]	...
LO—Length overall, min[H]	115 (4.5)
G—Gage length[I]	...
G—Gage length[I]	25 (1.00)
D—Distance between grips	65 (2.5)[J]
R—Radius of fillet	14 (0.56)
RO—Outer radius (Type IV)	25 (1.00)

Figure 3 ASTM D638 type IV tensile testing specimen.

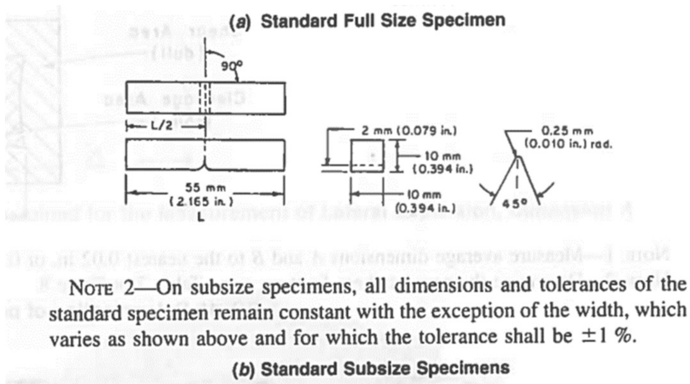


Figure 4 ASTM A370 Charpy Impact Test Specimen.

Specimens were varying based on the percentage infill and each single print can have only one infill percentage. The 20%, 40%, 70%, and 95% infills were chosen as the 4 different variables. There are a total of 6 different orientations and each single print has 4 specimens of each orientation. This creates 24 specimens for each print. The first batch of tensile specimen prints were labeled and can be seen in Figure 5.

Table 1 shows a partial list of the tensile specimens planned to be printed and tested for the regular PLA material. The list shows the variations in orientation and infill for 20% and 40% infill. All specimens were of type IV and the number of shells were kept at 2. The same configurations were repeated for 70% and 95% infill.

Figure 5 First Batch of Tensile Test Specimen.

Table 1 Coding for Tensile Test Specimens (partial list).

PRINT LOG - TENSILE TEST

ASTM STANDARD	TYPE	ORIENTATION	PLA MATERIAL	SHELLS	FACE	INFILL	FINAL CODE	SPECIEMNS PRINTED
D638	4	X	R	2	W	20.00	XW20	4
D638	4	Y	R	2	W	20.00	YW20	4
D638	4	Z	R	2	W	20.00	ZW20	4
D638	4	X	R	2	T	20.00	XT20	4
D638	4	Y	R	2	T	20.00	YT20	4
D638	4	Z	R	2	T	20.00	ZT20	4
D638	4	X	R	2	W	40.00	XW40	4
D638	4	Y	R	2	W	40.00	YW40	4
D638	4	Z	R	2	W	40.00	ZW40	4
D638	4	X	R	2	T	40.00	XT40	4
D638	4	Y	R	2	T	40.00	YT40	4
D638	4	Z	R	2	T	40.00	ZT40	4

Adding the PLA specimens with 70% and 90% infill, the total number of tensile specimens printed, tested, and analyzed for the regular PLA was 96. Varying the configuration in the same manner for the Tough material, the total number of tensile specimens was also 96. This resulted in 192 overall tensile specimens. Same procedure was planned for the impact test with a total of another 192 specimens for the Charpy test. Upon starting of the Charpy tests, it was clear that the impact strength for the regular PLA specimens is very low and lies around the lowest limit that the machine can measure. This can be due to the fact that the machine used is a high energy impact machine used for metals. This led to many zero readings and unreadable values for impact energy. It was decided to postpone the impact test for the regular PLA until a low energy impact tester is available. Therefore, the final number of specimens for Charpy was reduced to 96 based on testing only the Tough material. Figure 6 and Figure 7 show 2 prints of Charpy test specimens and their assigned code based on their print orientation.

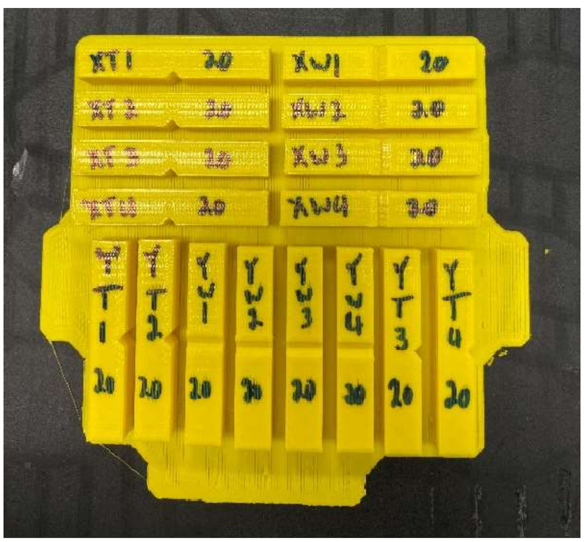


Figure 6 Charpy Specimen Orientation Coding (specimens printed along X & Y axes).

Figure 7 Charpy Specimen Orientation Coding (specimens printed along X. Y & Z axes).

Results

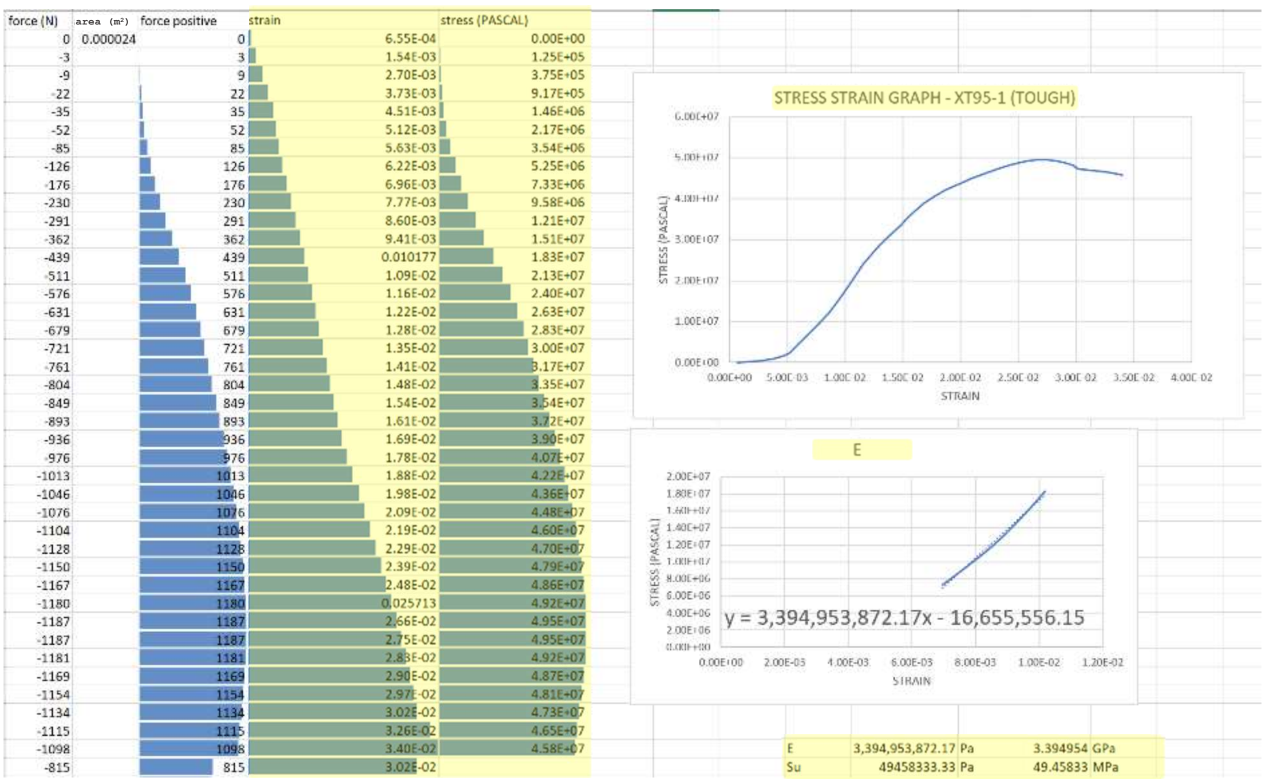
1. Tensile Test

Tensile test data for PLA and Tough PLA were collected for the different infill densities, and orientations. Data was used to plot the stress-strain curve, estimate Young's Modulus, and ultimate tensile strength for each print setting. A sample tensile test specimen is shown in Figure 8 (a) after breaking. The gained experience allowed the student to get a full understanding of the process and create a user guide to use the vertical test stand as seen in Figure 8 (b).

Figure 8 (a) Sample tensile test specimen (left), (b) Guide for test stand and extensometer (right).

A sample Excel sheet for processed data appears in Figure 9. It represents the tensile test results and associated plots for the first specimens of the 95% infill Tough material printed with its longest dimension directed along the x axis of the printer and its thickness laying on the build plate of the printer (XT95-1).The columns on the left side of Figure 9 represent the force as read by the load cell, in Newton, the corrected force value (switched the raw value to positive), the strain value as read from the extensometer, and the calculated stress in MPa. The stress-strain plot of these data is presented in the top right of Figure 9 and the linear portion of the plot was isolated in the middle right of the figure and a trendline was added to estimate the modulus of elasticity. The conclusion of the results for this specific specimen, namely the modulus of elasticity and the ultimate tensile strength, are presented at the lower right side of the figure. The same worksheet and analysis were repeated for the remaining 3 tensile specimens with the same configurations (XT95-2, XT95-3, and XT95-4) and for all

The Z axis prints noticeably underperformed compared to the X and Y axis prints while X and Y axis prints performed the same. As the Z axis prints have very minimal surface area for the layers to bind together it creates a much weaker part. The infill pattern for all specimens is the default, which is diamond pattern. Test data for all specimens were recorded, analyzed in a similar manner and the concluding results for the relation between ultimate tensile strength, for prints along X axis, and percentage infill, is reported in Figure 10. It was clear that the tensile strength is linearly proportional with the percentage infill of the specimen.



force (N)	area (m²)	force positive	strain	stress (PASCAL)
0	0.000024	0	6.55E-04	0.00E+00
-3		3	1.54E-03	1.25E+05
-9		9	2.70E-03	3.75E+05
-22		22	3.73E-03	9.17E+05
-35		35	4.51E-03	1.46E+06
-52		52	5.12E-03	2.17E+06
-85		85	5.63E-03	3.54E+06
-126		126	6.22E-03	5.25E+06
-176		176	6.96E-03	7.33E+06
-230		230	7.77E-03	9.58E+06
-291		291	8.60E-03	1.21E+07
-362		362	9.41E-03	1.51E+07
-439		439	0.010177	1.83E+07
-511		511	1.09E-02	2.13E+07
-576		576	1.16E-02	2.40E+07
-631		631	1.22E-02	2.63E+07
-679		679	1.28E-02	2.83E+07
-721		721	1.35E-02	3.00E+07
-761		761	1.41E-02	3.17E+07
-804		804	1.48E-02	3.35E+07
-849		849	1.54E-02	3.54E+07
-893		893	1.61E-02	3.72E+07
-936		936	1.69E-02	3.90E+07
-976		976	1.78E-02	4.07E+07
-1013		1013	1.88E-02	4.22E+07
-1046		1046	1.98E-02	4.36E+07
-1076		1076	2.09E-02	4.48E+07
-1104		1104	2.19E-02	4.60E+07
-1128		1128	2.29E-02	4.70E+07
-1150		1150	2.39E-02	4.79E+07
-1167		1167	2.48E-02	4.86E+07
-1180		1180	0.025713	4.92E+07
-1187		1187	2.66E-02	4.95E+07
-1187		1187	2.75E-02	4.95E+07
-1181		1181	2.83E-02	4.92E+07
-1169		1169	2.90E-02	4.87E+07
-1154		1154	2.97E-02	4.81E+07
-1134		1134	3.02E-02	4.73E+07
-1115		1115	3.26E-02	4.65E+07
-1098		1098	3.40E-02	4.58E+07
-815		815	3.02E-02	

E	3,394,953,872.17	Pa	3.394954	GPa
Su	49458333.33	Pa	49.45833	MPa

Figure 9 Sample tensile specimen datasheet for specimen XT95-1 Tough
Force, strain, and stress data with blue data bars (left). Stress-Strain plot (top right).
Elastic portion of the Stress-Strain plot (middle right). Modulus of elasticity (E) & ultimate tensile strength (S_u).

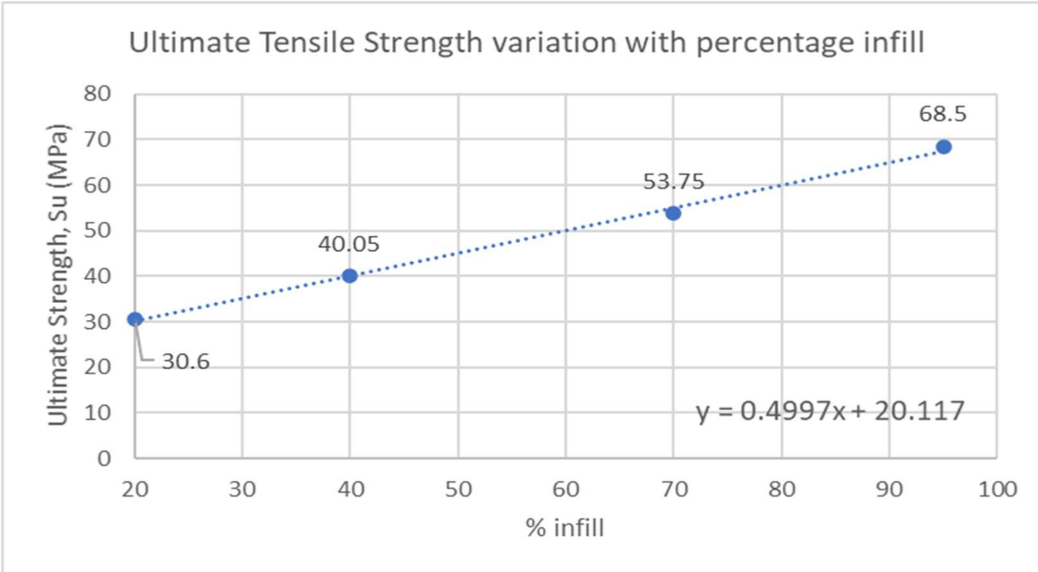


Figure 10 Ultimate Tensile Strength variation with percentage infill for PLA.

2. Impact Test

Results from the PLA tough specimens can be seen below in the form of a table and scatter plot. The scatter plot helps visually see the linear correlation between infill percentage and specimen toughness. The Z axis prints underperformed in the Charpy test just like in the vertical test stand test. A total of 192 different specimen data can be seen between the two sets of data. Table 2 and Figure 11 through Figure 13 show the results and plotted data from PLA tough specimens.

Table 2 PLA tough Charpy results.

ASTM STANDARD	ORIENTATI	PLA MATERIAL	SHELLS	FACE	INFILL	FINAL CODE	SPECIEMNS PRINTED	TEST 1 (IN*LBS)	TEST 2 (IN*LBS)	TEST 3 (IN*LBS)	TEST 4(IN*LBS)	AVERAGE (IN*lbs)
A370	X	T	2	W	20.00	XT2W20	4	7.8987	9.117	9.7266	8.5077	8.8125
A370	Y	T	2	W	20.00	YT2W20	4	7.2891	8.5077	7.8987	9.7266	8.355525
A370	Z	T	2	W	20.00	ZT2W20	4	3.6407	3.0332	3.0332	3.6407	3.33695
A370	X	T	2	T	20.00	XT2T20	4	8.5077	9.7266	8.5077	9.7266	9.11715
A370	Y	T	2	T	20.00	YT2T20	4	7.2891	7.8987	6.6805	6.6805	7.1372
A370	Z	T	2	T	20.00	ZT2T20	4	4.2483	3.6407	3.0332	3.6407	3.640725
A370	X	T	2	W	40.00	XT2W40	4	10.946	9.7266	9.7266	10.336	10.1838
A370	Y	T	2	W	40.00	YT2W40	4	7.8987	10.946	8.5007	8.5007	8.961525
A370	Z	T	2	W	40.00	ZT2W40	4	4.2483	4.8559	4.2463	3.6407	4.2478
A370	X	T	2	T	40.00	XT2T40	4	9.7266	8.5077	8.5007	9.7266	9.1154
A370	Y	T	2	T	40.00	YT2T40	4	9.117	7.2891	9.7266	8.5007	8.65835
A370	Z	T	2	T	40.00	ZT2T40	4	4.2483	4.8559	4.8559	4.8559	4.704
A370	X	T	2	W	70.00	XT2W70	4	10.336	12.777	10.946	10.946	11.25125
A370	Y	T	2	W	70.00	YT2W70	4	12.167	10.946	12.777	11.556	11.8615
A370	Z	T	2	W	70.00	ZT2W70	4	4.8559	4.8559	4.2483	6.6805	5.16015
A370	X	T	2	T	70.00	XT2T70	4	13.999	12.167	15.222	11.556	13.236
A370	Y	T	2	T	70.00	YT2T70	4	9.7266	9.7266	13.388	10.336	10.7943
A370	Z	T	2	T	70.00	ZT2T70	4	6.072	6.6805	6.6805	5.4639	6.224225
A370	X	T	2	W	95.00	XT2W95	4	14.611	15.834	17.058	19.509	16.753
A370	Y	T	2	W	95.00	YT2W95	4	16.446	16.466	17.671	15.222	16.45125
A370	Z	T	2	W	95.00	ZT2W95	4	3.6407	4.8559	7.2891	7.2891	5.7687
A370	X	T	2	T	95.00	XT2T95	4	14.611	13.999	13.388	16.446	14.611
A370	Y	T	2	T	95.00	YT2T95	4	13.99	14.611	14.611	14.611	14.45575
A370	Z	T	2	T	95.00	ZT2T95	4	7.898	6.072	6.072	5.4639	6.376475

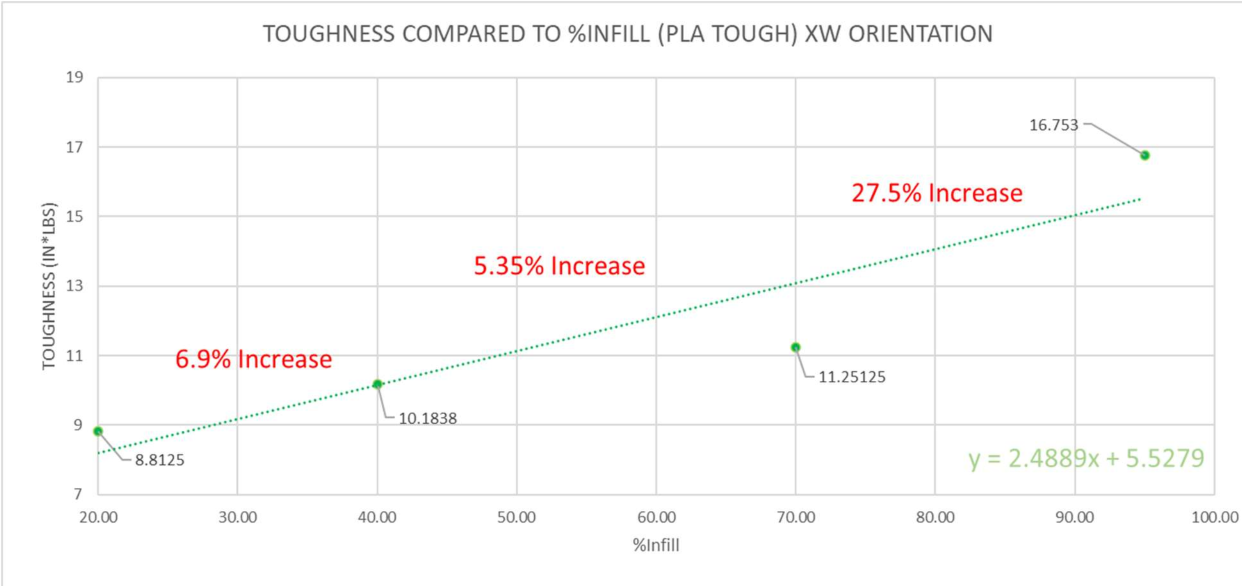


Figure 11 Charpy test results for PLA tough X-axis prints.

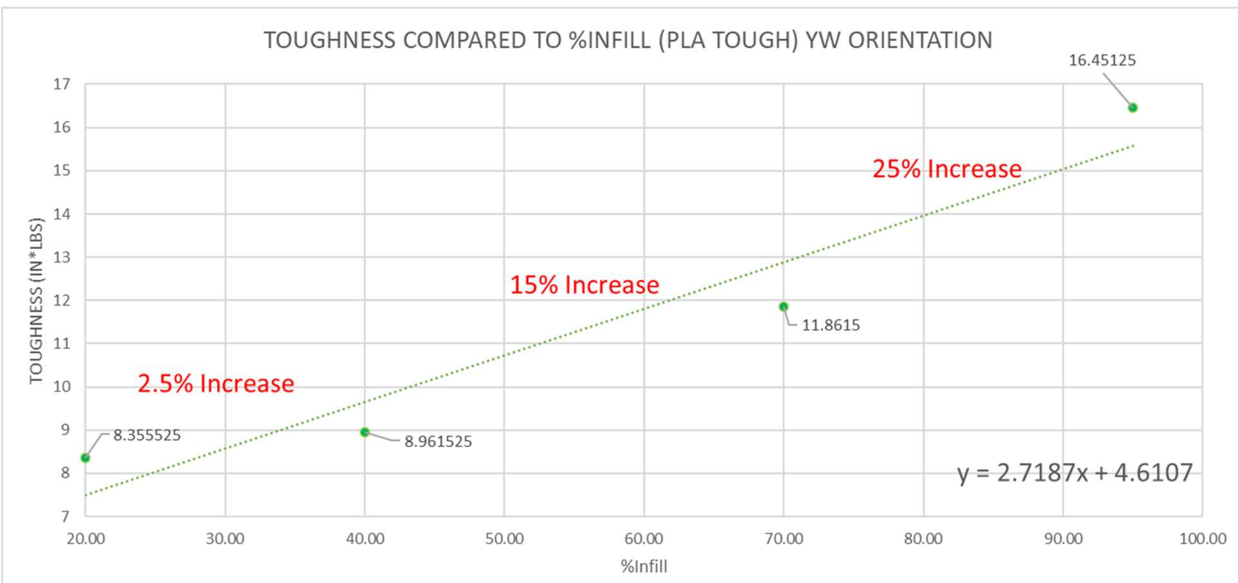


Figure 12 Charpy test results for PLA tough Y-axis prints.

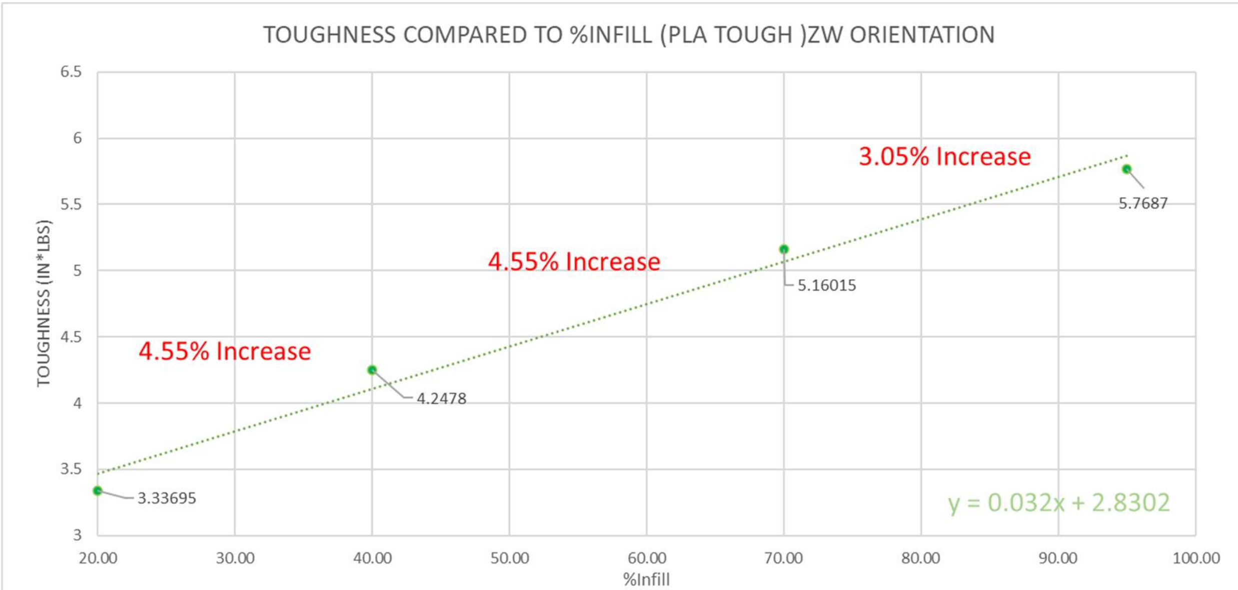


Figure 13 Charpy test results for PLA tough Z-axis prints.

The analysis of test results showed correlations between the increase in the percentage infill (density) and the increase in toughness, as well as the tensile strength. It was clear that printing along the longer edge of the specimen gives the highest strength. The values of the mechanical properties including tensile strength and impact strength were comparable to commercially available data. In the current stage of this project, tensile strength, modulus of elasticity, and impact strength for multiple 3D printing geometric patterns will be determined and compared. The results obtained so far indicate that linear, diamond, and hexagonal infill patterns are the ones with the highest strength values. Upon completion of the tests with different infill geometric patterns, the strength-pattern relationship will be established. The density of specimens with each pattern will be recorded and a strength to density measure will be developed.

Conclusions

As seen from the experiment details above, the goals set for this project were achieved as a group of ET graduating seniors were introduced to the concepts of testing of materials according to the ASTM standards and simple research was conducted. The team developed a good understanding of the methodology and standards of the tensile and impact tests and successfully used the involved data acquisition systems and relevant software. They were further able to analyze a significant number of results and compare results to commercially available data. Based on the completed experiments, so far, students could conclude that configuration of 3D printing can deliver the products with the various mechanical properties. Setting these configurations properly allows producing parts that meet the required strength while keeping the cost, weight, and time at minimal values. This helps in creating more efficient products that not only help in the modern industry, but also, helps in the space exploration missions led by NASA. As expected, percentage infill was linearly proportional to the mechanical properties. So far, linear, diamond, and diamond patterns delivered higher mechanical properties with respect to other available patterns.

Further experiments will be performed to investigate the effect of geometric patterns on the mechanical properties.

Acknowledgement

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Bibliography

[1] Zacharie Day, Ahmad Fayed, Investigation of Mechanical Properties for Static and Dynamic Loaded 3D Printed Products, LaSPACE LURA 2020/2021 project report.

[2] "ASTM D638-14. "*ASTM International - Standards Worldwide*, www.astm.org/Standards/D638.htm.

[3] Ali Ashter, Syed. "Charpy Impact Test." Charpy Impact Test - an Overview | ScienceDirect Topics, 2019, www.sciencedirect.com/topics/engineering/charpy-impact-test.

[4] Berman, Barry. "3-D Printing: The New Industrial Revolution." Business Horizons, Elsevier, 3 Dec. 2011, www.sciencedirect.com/science/article/pii/S0007681311001790.

[3] Bryan, William. "Future Rocket Engines May Include Large-Scale 3D Printing." *NASA*, NASA, 11 Sept. 2020, https://www.nasa.gov/centers/marshall/news/releases/2020/future-rocket-engines-may-include-large-scale-3d-printing.html

[4] "AM for Space Archives." *3D Printing Media Network - The Pulse of the AM Industry*, https://www.3dprintingmedia.network/category/aerospace/space-exploration/.

[5] Fekete, Imre, et al. "Highly Toughened Blends of Poly(Lactic Acid) (PLA) and Natural Rubber (Nr) for FDM-Based 3D Printing Applications: The Effect of Composition and Infill Pattern." Polymer Testing, vol. 99, 2021, p. 107205., https://doi.org/10.1016/j.polymertesting.2021.107205.