Effect of Common Print Parameters on the Mechanical Properties of the Produced Parts

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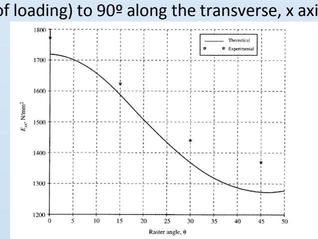
Project Objectives and Goals

The goal of this project was to begin the process of establishing a Processing-Structure-Properties-Performance relationship for FDM printed parts. This relationship was established by independently varying common print parameters of layer orientation and extrusion temperature when printing ASTM D3039 coupons for tensile tests. Digital Image Correlation (DIC) was used as a supplementary strain measurement technique to gain a better understanding of the full field deformation of the entire visible surface of tested specimen.

Background

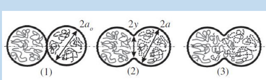
3D printing has recently become the cornerstone of rapid prototyping, being able to turn a CAD model into a physical model in a few hours. Additional research is required to quantify the effect of print parameters to fully transition from a prototyping technique to viable manufacturing technique. Prior to starting this research a comprehensive literature review was performed to establish the state of the art in this field. The literature review indicated that layer orientation and temperature were the easiest parameters to correlate their effects to the final performance of the part [1-8].

Orientation refers to the angle the filament is deposited onto a 3D printed part as the print head moves along the toolpath. In this study, the angle was defined as increasing from 0º along the longitudinal, y axis (axis of loading) to 90º along the transverse, x axis.



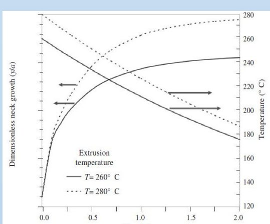
Filament angle vs. Modulus [2]

In this study, the extrusion temperature, more accurately the extruder temperature, was chosen to be modified. Prior research found that temperature had a strong effect on the properties of the parts, with bond strength and bond length increasing as temperature increased as shown below [3,4]. This increase in bond length can be viewed as a decrease in air gap, another common print parameter which describes the distance between adjacent filament stands as they are deposited, as shown below.



Adjacent filament bonding stages above [3]

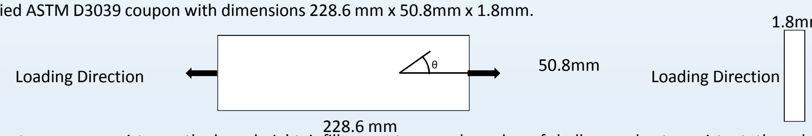
Effect of extrusion temperature on bond length to the right [3]



Filament material was also chosen as a parameter in this study to connect the effects of parameters above to material properties. Previous work tested a single strand of filament in tension, comparing these values to parts produced using the same feedstock material [5]. The material data collected was compared to existing data of parts of the same material produced through a typical extrusion process.

Experimental Setup

To determine the effects of the parameters described in background, several rounds of coupons were printed using a modified ASTM D3039 coupon with dimensions 228.6 mm x 50.8mm x 1.8mm.



In order to ensure consistency, the layer height, infill percentage, and number of shells were kept consistent; the values for these settings are shown below. The extrusion temperature coupons consisted of Polylactic acid (PLA) and Acrylonitrile Butadiene-Styrene (ABS). The PLA specimen were printed on Makerbot Replicator 2 printers, while the ABS specimen were printed on Makerbot Replicator 2X printers with Makerware used to prepare the prints. The orientation coupons consisted of Nylon, Acrylonitrile Butadiene-Styrene (ABSi), and Polycarbonate (PC). All orientation coupons were printed on a Fortus 400mc printer from Stratasys using Insight to prepare the specimens.

Print Setting	Value
Infill Percentage	100%
Layer Height	0.1mm
Number of Shells	2

Parameters applied to each Coupon

Material	Extrusion Temperatures (°C)
ABS	210, 220, 230,240,250
PLA	Initial Prints: 190, 205, 220, 235, 250 Final Prints: 210, 220,240,250

Temperature parameters tested for PLA and ABS

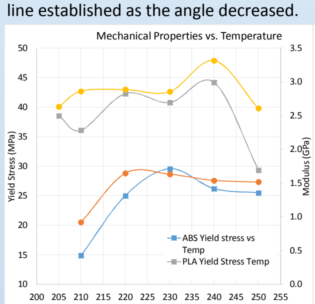
Material	Orientations
Nylon	0, ±30, ±45, ±60, 90, 0/90
ABSi	0, ±30, ±45, ±60, 90, 0/90
Polycarbonate (PC)	0, ±30, ±45, ±60, 90, 0/90

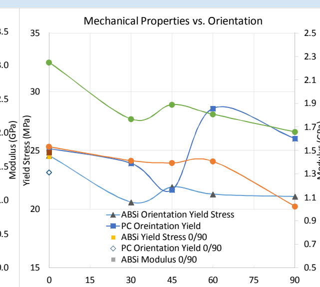
Orientation parameters tested for Nylon, ABSi and PC

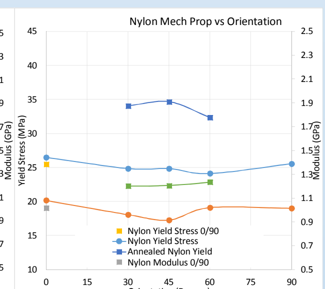
The coupons were tested on a Instron 5984 load frame equipped with a 150kN load cell. A majority of the tests were carried out using a video extensometer as the strain measurement device. Digital Image Correlation (DIC) was used on one coupon per parameter group to gain a better understanding of the deformation as the test occurred.

Results & Discussion

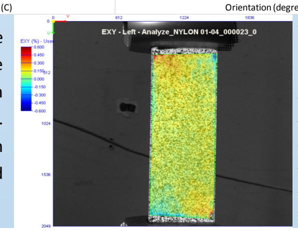
The graphs below display the yield stress on the primary axis and modulus of elasticity on the secondary axis with the parameter tested on the x-axis. The 0/90 specimen were plotted as 0 degree specimen to prevent disruption of the trend line established as the angle decreased.



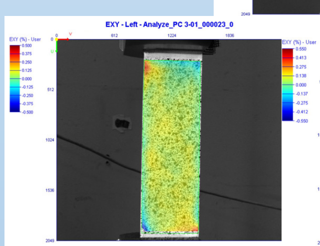


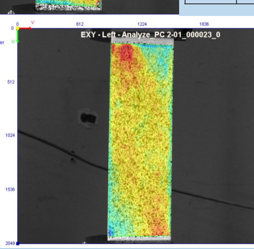


DIC images for the following orientations are shown (clockwise from right): 0, ±30, and ±45. Strain accumulations can be seen in the large red and blue colored areas.



Material	Test Modulus (GPa)	Test Yield Stress (MPa)	Published Modulus (GPa)	Published Yield Stress (MPa)	Percent Difference Modulus (%)		Percent Difference Yield Stress (%)	
ABS	1.65	29.59	1.0-2.65	13.0-65.0	0.63	-0.38	1.28	-0.54
PLA	3.09	44.45	.230-13.8	16-114	11.42	-0.79	1.55	-0.64
ABSi	1.53	24.57	1.92	*	-0.20		*	*
Nylon	1.08	26.5	.08-64.1	9.5-170	12.53	-0.98	1.79	-0.84
PC	2.25	25.17	1.79-3.24	58.6-70	0.26	-0.31	-0.57	-0.64





The data in the table above contains the percent difference between the published values for an extrusion process and the FDM printing process. The data points for the test modulus and yield stress were taken at the manufacturer's default print settings. The raw data represents parts made of the filament material using a typical extrusion process [9,10]. The asterisks represent unavailable data values.

Conclusions

The mechanical properties of the orientation specimen decreased as the orientation angle increased, albeit the drop off not being as sharp as expected. The temperature specimen exhibited a bell shaped curve, which did not fit the trend. It was expected to display an increase in both modulus and yield stress as temperature increases. As the temperature increased past the optimal temperature the material properties started to drop off sharply, indicating that the structure of the filament is heavily influenced by the temperature. Further tests are needed to further advance the Processing-Structure-Properties-Performance relationship for FDM parts.

The percent difference data presented in the results section does not provide much insight into the effect of the FDM process on the final parts simply due to the wide range of possible values for each material after an extrusion process.

Future Studies / Recommendations

To continue the establishment of the Processing-Structure-Properties-Performance relationship, additional layer orientations are in the process of being looked at. This includes unidirectional tests to further establish the link between change in angle and the performance of the parts. SEM images from collaborators showed that the use of shells had an effect on the strength of the part and as such future tests will not make use of shells.

To further explore the effect of temperature, controlled annealing of the printed coupons is a potential direction to head in. The Nylon data gathered in this test provided insight into the effects this could have on the performance of the produced parts, causing a change in both modulus and yield stress. Torsion coupons are in the process of being designed to expand the FDM tests beyond tension testing.

To further the material processing area of the research, injection molded parts are being tested alongside FDM parts of the same geometry with the aim to compare the mechanical properties between injection molded plastics and FDM prints.

Acknowledgments

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