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Title: Structure Property Studies for Additively Manufactured Parts

Author(s): Milenski, Helen M
Schmalzer, Andrew Michael
Kelly, Daniel

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Name: Helen M. Milenski

Program: Department of Energy, Community College Internship

School: University of New Mexico, Los Alamos

Group: C-CDE

Mentors: Dan Kelly and Andrew Schmalzer

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Structure Property Studies for Additively Manufactured Parts

Since the invention of modern Additive Manufacturing (AM) processes engineers and designers have worked hard to capitalize on the unique building capabilities that AM allows. By being able to customize the interior fill of parts it is now possible to design components with a controlled density and customized internal structure. The creation of new polymers and polymer composites allow for even greater control over the mechanical properties of AM parts. One of the key reasons to explore AM, is to bring about a new paradigm in part design, where materials can be strategically optimized in a way that conventional subtractive methods cannot achieve. The two processes investigated in my research were the Fused Deposition Modeling (FDM) process and the Direct Ink Write (DIW) process. The objectives of the research were to determine the impact of in-fill density and morphology on the mechanical properties of FDM parts, and to determine if DIW printed samples could be produced where the filament diameter was varied while the overall density remained constant.

FDM is the most commonly known AM process because of its popularity with home users and the ‘maker movement’ where inventors and crafters use table top 3D printers for a wide variety of purposes. In recent years this enterprise has brought AM into the mainstream through its claims of revolutionizing everything from medicine and commercial manufacturing to clothing design and food. In any of these pursuits the keys to AM success is fast production, ease of design modification, and reproducibility. FDM has some challenges in these two areas to overcome before it can truly live up to its potential, such as instrument inertia and feedstock variability, which can affect the properties of the final part.

In order to study the effect of the in-fill pattern on the dimensional stability of the parts, I produced two distinct prismatic shapes, rectangular and cylindrical with several in-fill pattern styles at three different percentages of “in-fill”. The choice of the cylindrical versus rectangular prism allows for comparison of how stress concentrations in rectangular parts might be affected by shrinkage and warpage during solidification of the parts. The choice of pattern, percentage of in-fill, and orientation of the structure are studied to identify their effect on overall mechanical properties. I used a commercial table top AM FDM machine, the Airwolf HD2x 3D printer, to produce Acrylonitrile Butadiene Styrene (ABS) samples for these tests. ABS was used since it is currently the most popular FDM feedstock used in tabletop 3D printing, and current data on mechanical response on ABS parts would be beneficial to the 3D printing community. The ABS is manufactured by Toner Plastics, 35 Industrial Drive East Longmeadow, MA 01028, and has a measured density of 1.015 g/cc. This material has a melting point of between 200 and 220 degrees Celsius.

The pattern variety of in-fill designs consisted originally of *grid, triangle, concentric, hexagonal, and lines* created from the open source software, Matter Control 1.2. This software allows for remote control of the 3D printer, as well as the generation of the .gcode made from the sliced .stl file. The .gcode is the direct instructions for the x, y, and z axis tool path and extrusion profile that the Airwolf will use to build the part. The software calculates a gcode for in-fill pattern based on the percent of in-fill and the type of structure that is selected. The software generates build parameters that can be modified to optimize the print, such as print speed, extrusion rate, retraction speed, and several others. The samples of each pattern were produced with 15%, 30%, and 45% in-fill. The initial sample production angle orientation chosen was 45 degrees. The top and bottom layers of each part were not included, to prevent boundary effects on the mechanical response of the part.

Optimal print(er) settings for ABS must be included in the Matter Control for generating quality parts. The bed plate and extruders were set to 115 and 235° Celsius, respectively. The extruder speed for building the in-fill was 25 mm/s. The perimeter was printed at 30mm/s and was only one layer wide, to prevent as little interference on the mechanical response as possible. The speed for retraction and non-print moves was 100mm/s, to decrease the amount of print time. The first layer speed was set to 15mm/s, which is typical because the first layer often has trouble adhering to the build plate. The maximum range of carriage (x and y directions) speed for the extruder of the Airwolf is 150mm/s, and is constrained to a build area of 300mm by 200mm and a build height of 300mm. The Airwolf HD2x model has the capability of dual extrusion, but in order to ensure that the secondary extruder did not interfere with the printing the tip of this extruder was removed. The second tip can ruin a print by impinging the surface or creating unwanted reheating of the part surface. The nozzle diameter is 0.5mm; however each layer was printed to be 0.2mm thick, with a 0.04 mm overlap. Temperature was not consistent across the build plate throughout the build process due to room temperature fluctuations and heater location in the bed itself. The temperature fluctuations induced by the air conditioning was prevented by installing a shield on top of the printer, which redirected the flow of air. Some of the uncontrollable variables of the production were room temperature fluctuations, printer calibration, and material humidity absorption. The effects of these were mitigated as best as possible within reasonable expectation.

Sample masses (M) were measured with a Mettler Toledo Balance with an error standard of +/-0.01g. The volume (V) of each sample was measured using a metric caliper with an error standard of +/-0.002cm. From these measurements the density (ρ) of a part was calculated as $\rho = M/V$. This value was compared with the theoretical values of volume calculated with the actual mass and the actual material density.

Rectangle				
In-Fill design	Fill percent	In-Fill Mass (g)	In-Fill Volume (cm^3)	In-Fill Density (g/cm^3)
Grid	15%	4.10	30.20	0.1358
	30%	9.19	29.44	0.3121
	45%	14.62	29.45	0.4964
Triangle	15%	3.99	30.11	0.1325
	30%	9.17	29.84	0.3073
	45%	14.59	29.67	0.4917
Concentric	15%	4.66	29.81	0.1563
	30%	9.84	30.06	0.3274
	45%	11.33	29.48	0.3843
Hexagonal	15%	2.31	29.84	0.0774
	30%	5.73	29.53	0.1940
	45%	9.49	29.37	0.3232
Lines	15%	4.05	29.85	0.1357
	30%	9.09	29.80	0.3050
	45%	14.81	29.31	0.5052

Cylinder				
In-Fill design	Fill percent	In-Fill Mass (g)	In-Fill Volume (cm^3)	In-Fill Density (g/cm^3)
Grid	15%	4.39	30.74	0.1428
	30%	9.59	30.74	0.3120
	45%	14.78	30.85	0.4790
Triangle	15%	4.50	30.73	0.1454
	30%	9.63	30.73	0.3134
	45%	14.58	30.87	0.4724
Concentric	15%	5.08	31.07	0.1635
	30%	10.27	31.05	0.3308
	45%	15.38	31.07	0.4951
Hexagonal	15%	2.74	30.54	0.0897
	30%	6.14	30.54	0.2010
	45%	9.59	30.54	0.3140
Lines	15%	4.48	30.43	0.1472
	30%	9.66	30.42	0.3176
	45%	14.89	30.45	0.4890

It can be clearly seen that despite selecting a percent of in-fill pattern for the samples, the software is unable to exactly structure the pattern to the desired percent. This variability can make designing parts with precise density difficult. The gcode generating software that creates the in-fill patterns can usually do so within a range of a few percent of the amount selected. However, this does not hold in the case of the *hexagonal* in-fill pattern. In each case of the *hexagonal* in-fill, samples have a much lower mass than for other in-fill types causing a large deviation from the expected density. This trend is seen with both the rectangular shape and the cylindrical shape. On average the *hexagonal* pattern shows a 10.7% lower part density than the target in-fill percent. The *hexagonal* pattern cannot be relied on to accurately represent the selection of in-fill percent, and likewise also greatly reduces the quantity of material used to create the inner structural support. This could be very important to consider in cases where the quantity of material is a significant factor. However, in most cases part weight and strength are as critical to the performance as density. Therefore, the *hexagonal* in-fill pattern must be viewed in light of the mechanical testing data versus the other patterns.

In regards to the reproducibility of FDM parts, several of the differently patterned pieces experienced varying degrees of warpage in a directional alignment with the orientation of the in-fill pattern. In the cases where this was strongly noted the amount of 'peel up' was also greater. The phenomenon of 'peel up' is where the build material loses adhesion with the build plate as the process of laying down material continues. 'Peel up' is prominent at adhesion points that include angles, thin pieces of material, or bridges in the part. We can only see measurable 'peel up' in the rectangle shapes. It is interesting that the pattern that yielded the largest amount of warpage as well as 'peel up' was the *triangular* pattern. These features were noted in the hexagonal in-fill, but they were only mild in comparison to the other pattern samples.

DIW is an AM process that enables the production of structured elastomeric materials. The feedstocks for this process are thermosetting polydimethylsulfone (PDMS) fluids that are filled with a networking additive such as fumed silica to provide a yield stress, but are not so filled that shear-thinning behavior is lost. The yield stress keeps the fluid from flowing once it is extruded onto the build plate. This property is exceptionally important to the bridging capability as a structure is built up layer upon layer. The material must be able to lie upon a previously deposited layer without excessively deforming that layer or itself. This property must be stable over varying structure heights and complexity until the printing is complete and the curing process can be performed. The PDMS resin Dow Corning SE1700 provides the needed yield stress while retaining enough shear thinning to allow extrusion.

The DIW printing was performed with an Aerotech linear positioning platform as well as the Aerotech Motion Controller and Computer Numerical Control (CNC) software. This equipment was accompanied by a Nordson Electronic Fluid Dispenser (EFD) attached to barrel syringes with gauged nozzle tips in order to produce specific PDMS filament diameters. Several parameters were entered into a LabVIEW program in order to produce a .gcode file for a layer-wise *face centered cubic* (FCC) pattern that would maintain the density of the part from one filament diameter to another. Each small pad shaped sample is built of a small cross hatch pattern that has a continuous extrusion from beginning to end of the part, so as to eliminate filament inconsistency due to non-linear stress growth of the polymer upon repeated starting and stopping of extrusion. We studied the density of samples made from the gauge sizes 20G (584.2μm), 22G (406.4μm), 25G (254.0μm), and 27G (203.2μm).

Measurements of DIW parts (in microns) are below:

Face				
Gradient Analysis Data	20G (584.2 µm)	22G (406.4 µm)	25G (254.0 µm)	27G (203.2 µm)
Filament Diameter	557.15	354.55	218.51	201.16
Gap Measurement Width	662.21	442.72	257.62	185.1
Side				
Filament Side Layer Count	16	24	38	48
Gap Height	397.95	320.25	147.82	178.97
Gap Width	695.22	432.68	237.66	218.25
Filament Diameter	503.43	354.32	241.07	126.59
Total Height	7307.14	7490.49	7660.71	7368.27

Using the measurements gained from the micrographs we can calculate the volume of a row as such,

$((n-1)\ D^2\ L\ (1+\alpha)) + ((\pi D^2/4)\ L)$ = total row volume.

Where n is the number of filaments, D is the filament diameter, L is the filament length, and α is the gap dimension divided by the diameter.

We can calculate the total volume of polymer in a row by;

$((n\pi D^2)/4)\ L$= total polymer row volume.

Knowing these two values we can calculate for the volume of air in each row by;

Total row volume - total polymer row volume = total volume of air.

Taking the total volume of air divided by the total volume, gives the value of Φ_{air}, just as taking the total volume of polymer divided by the total volume give the value of $\Phi_{polymer}$, such that,

$1 = \Phi_{air} + \Phi_{polymer}.$

The density for each of the gauge sizes can be calculated using the formula:

$\rho_{row} = (\rho_{air}\ \Phi_{air}) + (\rho_{polymer}\ \Phi_{polymer})$

The density values DIW PDMS pads formed using each nozzle gauge size are shown below.

Density	20G (g/cm^3)	22G (g/cm^3)	25G (g/cm^3)	27G (g/cm^3)
Measurement with formula	0.42047	0.40522	0.41455	0.46784

The part density is seen to be fairly stable at ~0.42 g/cm^2 for each of the filament diameter produced according to gauge size. The variation can be attributed to the necessity of adjusting the speed rate of the linear platform movement and the air pressure of the fluid barrel in order to maintain filament integrity throughout the build of the part.

In each AM process trends in density are related to the structure of the part. In the FDM process the overall shape and reproducibility can be altered greatly by the software parameters set by the user. The software generates the .gcode tool path meant to give an approximation of the in-fill pattern at the desired in-fill percent. However, it is clear from the analysis of FDM parts that this approximation is not sufficient when the mechanical properties related to density are concerned. The hexagonal in-fill pattern exhibited the most deviation from the selection and because of that it may have some beneficial uses if it can be seen to have equivalent structural integrity relevant to patterns that require more material for the inner support. It is also noted that the orientation as well as pattern design of such in-fill can cause or intensify warpage and peel-up. Optimizing the orientation and the in-fill pattern relative to the design of a part can significantly reduce these alterations and provide for more reproducibility in manufacturing with AM.

The DIW process allows for structure to be controlled as a variable with a consistent density from part to part. With the assistance of the LabVIEW program a toolpath is generated according to the desired diameter of filament based on the nozzle gauge size in an attempt to produce pads of equivalent density. Samples at the four gauge sizes had an approximate density of 0.42 g/cm^3. The deviation from consistent density from pad to pad can be explained by the variation in both the linear positioning speed and air pressure to the feedstock. This occurs because manual adjustments must be made incrementally as the production is occurring so as to maintain the integrity of the filament over the entire build of the part.