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Reviewed Paper

LARGE SCALE FUSED DEPOSITION MODELING: THE EFFECT OF PROCESSING PARAMETERS ON BEAD GEOMETRY

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Abstract

This paper considers processing parameters that affect bead geometry in large-scale Fused Deposition Modeling (FDM). A BAK ExOn8 single screw mini extruder is used to deposit controlled thermoplastic beads on a custom made heated build platform specifically design for studying bead deposition. This study considers nozzle height above the build platform, extruder screw RPM, platform speed, and polymer type. Deposition is performed using an unfilled commercial copolyester, unfilled ABS, and filled ABS with 13% short carbon fibers. Bead cross sectional area and shape are measured to evaluate flow rate and melt distortion. Of particular interest is the dependence of bead shape on the inclusion of short carbon fibers. Shape metrics including horizontal and vertical swell, aspect ratio, and convexity ratio are used to quantify the shape of the bead cross section. Measured results show significant variability in cross section geometry, supporting the need for quantifying these effects in order to create a successful large-scale system.

Introduction

The Fused Deposition Modeling (FDM) technology has the capacity to redefine the manufacturing process as we know it. Prototype parts can go from the drawing board to physical realization in a matter of minutes or hours, making it possible for users to iteratively design geometrically complex and innovatively refreshing parts in industries where iteration and innovation have been previously limited. Unfortunately, the current FDM technology is limited to the scope of prototyping and modelling due to the limited mechanical integrity of the polymers used to produce parts compared to parts manufactured using traditional methods and materials. In addition, the build size of typical FDM machines is currently smaller than is feasible for some industrial applications, requiring a simultaneous effort to improve the material properties of FDM printed parts while also increasing the build volume.

Large scale FDM is a new technology, with few published papers including research on semi-automated construction deposition [1] and laying concrete foundations [2]. Here we use the term ‘large scale’ to indicate FDM processes that use a polymer extruder to deliver the bead of material onto the build surface with polymer deposition rates in the pounds per hour range. Large scale FDM extruders commonly have a nozzle exit that is much larger than the typical desk top printer (i.e., having a diameter in excess of ¼ inch). Oak Ridge National Labs is aggressively pursuing large scale FDM, as evidenced by a prototype FDM carbon fiber reinforced printed car chassis at IMTS 2014 [3]. Many parameter studies have been conducted on small scale FDM systems to identifying key aspects of systems which affect the material properties of the printed part. Such studies include parametric analyses of processing parameters including temperature, raster height, raster width, flowrate, nozzle height, and nozzle/platform speed [4], as well as studies examining specific aspects of the process such as inter-layer bonding

[5], effects on fiber reinforced prints [6], and tooling applications [7]. However, no current references exist which assess the effect of FDM processing parameters on printed outcomes, and the scaling of the technology from prototyping and modeling to manufacturing and industrial use.

The goal of this paper is to examine a large scale FDM system with a focus on processing parameters to determine the effects of these parameters on printed bead shape. The results from this study are expected to aid in the design and fabrication of large-scale printed parts, where issues related to voids, inter-layer adhesion, polymer sensitivity to parameters, and printing resolution are of interest. This study also considers differences in the application of FDM between small and large scale, specifically aspects of the process which must be altered in order to apply the technology to larger printed parts.

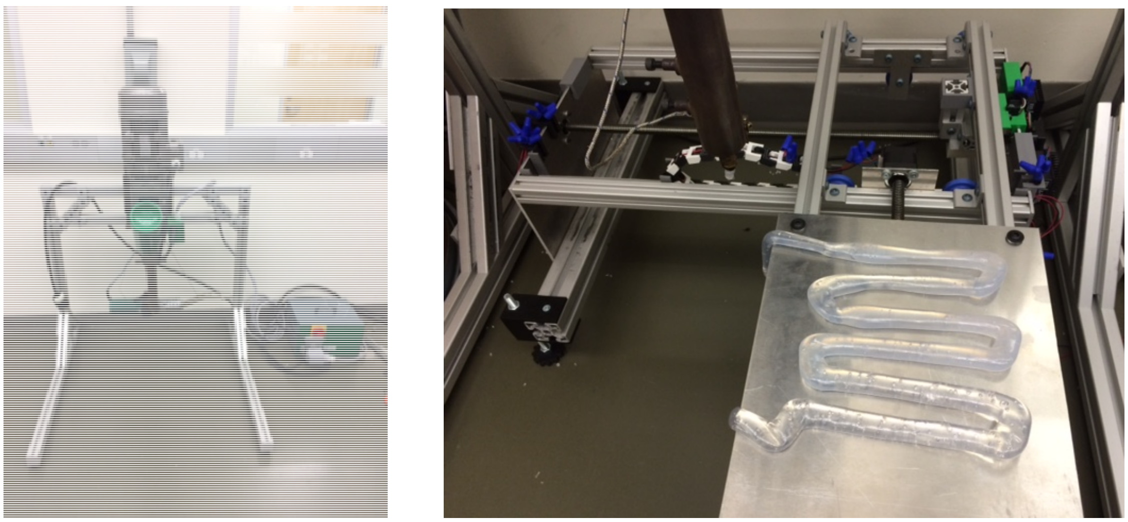
System Definition and Sample Preparation

An FDM system can be separated into two subsystems: 1) an extrusion system which accepts, melts, and extrudes polymer, and 2) a platform structure on which the printed part is built layer by layer.

The extrusion system used in this work is an Exon 8 Single Screw Extruder, manufactured by HapCo, Inc [8]. Here the mini extruder accepts polymer pellets into a heated screw, which then melts the material before extruding molten polymer at the nozzle exit. This extruder is capable of producing 13 pph HDPE and can be heated to common FDM temperatures of ~230°C. Several modifications were made to our extruder to adapt it for use in FDM, including rotating the hopper to maintain a uniform pellet feed condition, and modifying the extruder screw entrance region to provide a greater surface area of impingement on the feeding screw flight. These modifications highlight a key difference between small and large scale deposition, mainly that pellets are used instead of filament due to the high volume production; and, with the use of pellets, it is more difficult to operate the system at steady state than when using a filament.

A translation platform was designed and fabricated in-house which has two automated, 18” axes that translate using NEMA 14 stepper motors and ACME 10½” steel translation screws. Communicating with a desktop computer is facilitated using a LabVIEW interface. The result of this assembly is a semi-automated two axis system which has 18” of movement in both the ‘x’ and ‘y’ directions with velocities up to 15 mm/s, and is fully programmable using LabVIEW. As a demonstration of the current capabilities of small scale FDM, specific components of our system were designed and printed using a MakerBot Replicator 2X [9]. Here we limit the use of FDM to relatively small parts with little or no applied load so that stresses do not exceed acceptable values of the polymer. The build plate itself is created using two 1/8” aluminum plates with a flexible heating pad located in between, and insulation between the bottom plate and the heating pad to ensure the majority of the heat energy is transferred to the top deposition plate. The extruder assembly and translation platform appear in Figure 1.

Polymer beads were printed with the system in Figure 1 with various parameter settings using as needed for our study. Three polymer materials were selected for this study, specifically neat ABS (provided by Polyone Corporation), 13% Carbon Fiber Filled ABS (also provided by PolyOne Corporation), and a commercial copolyester designed for additive manufacturing (provided by an unspecified supplier). Parameters examined in this study include nozzle height (i.e., the distance between the nozzle and the table), table velocity, and ExOn8 extruder screw RPM (cf. Table 1). Instruction code was generated in LabVIEW which translates the platform similar to the pattern created in typical small scale FDM systems, where a relatively large spacing is maintained between printed beads to avoid bonding between individual beads. Our translation system also has a manual ‘z’ height adjustment so that layers of beads could be printed; however, the results presented here are form beads in one layer only. Printed beads were allowed to cool before being removed from the build plate so as not to distort the shape prior to solidification.



(a) (b)

Figure 1. Large scale FDM system at Baylor University: (a) Exon8 extruder assembly and (b) 2-axis deposition platform.

Table 1. Parameter settings for large scale deposition study.

Polymer Type	Screw RPM	Nozzle Height	Table Speed
commercial copolyester	20	1.5 mm	5 mm/s
neat ABS	40	3.25 mm	10 mm/s
ABS with 13% CF	60	5 mm	15 mm/s
-	80	-	-

In this study, printed beads are cooled and removed from the build plate, then cut normal to the print direction to yield a bead cross section for analysis using imaging software. A slow speed saw was used to cut cross sections from the beads in order to minimize adverse effects from the cuts in the cross section analysis, and in some cases cross sections were dyed to ensure image contrast with the image background. Each image was then uploaded and converted to an array of perimeter values based on the pixel positions at the boundaries, and adjusted to the scale of the image before being analyzed for specific geometry criteria.

Experimental Results

Several geometric and processing factors were measured from the bead cross-section images where data for each set of processing parameters is the average of three samples. The first processing factor considered is flowrate, with a focus on what effect changing parameter settings has on the volume of polymer being deposited on the platform. To calculate flowrate, the area of each cross section was measured and multiplied by the platform velocity, giving values of volumetric flow rate in mm^3/s. A comparison of the freestream flowrate without deposition, as well as calculated flowrates for all parameter settings, is shown in Figure 2.

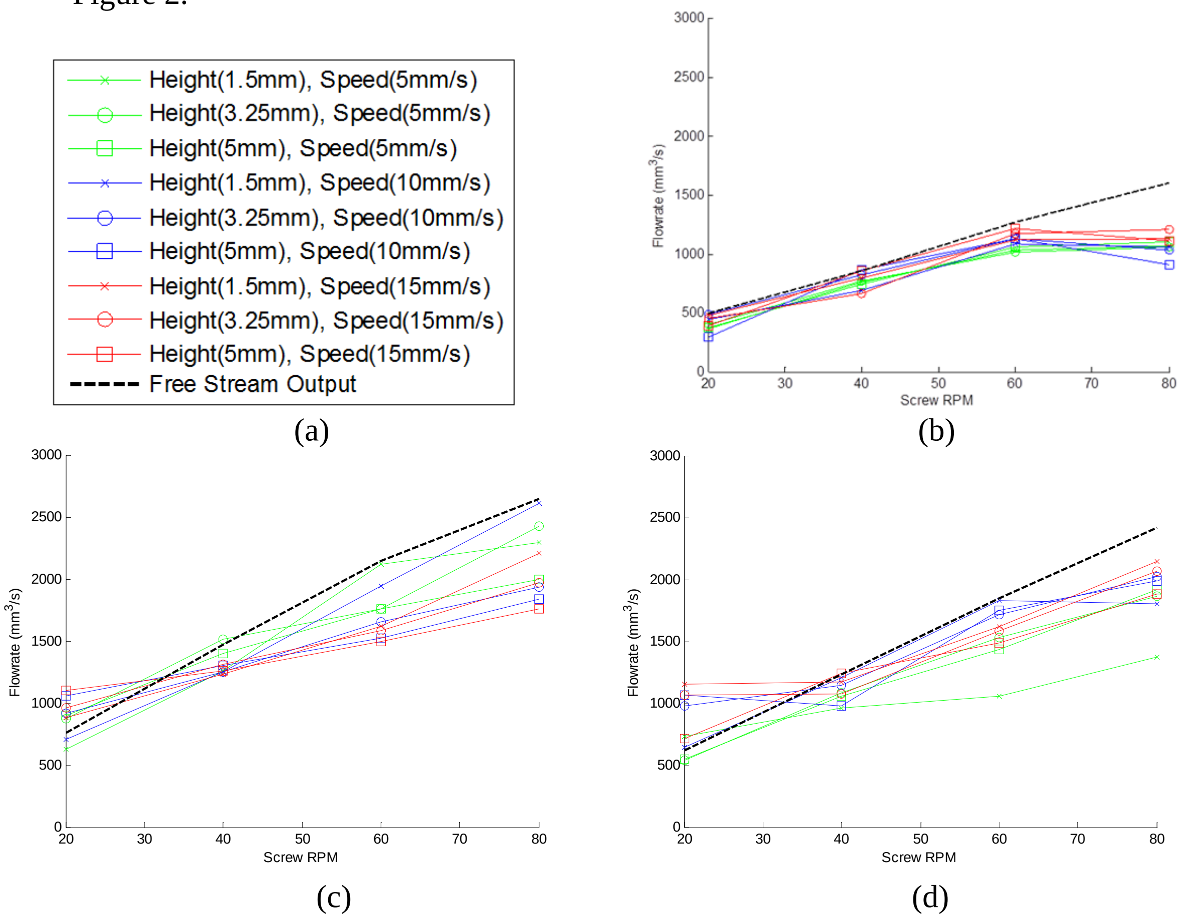


Figure 2. Calculated volumetric flowrate plots with (a) legend for (b) commercial copolyester, (c) Neat ABS, and (d) 13% Carbon CF ABS.

Several important aspects are present in these flowrate plots in Figure 2. First, note that the freestream flowrate is expected to create a theoretical upper bound as long as the table velocity isn't higher than the velocity of the polymer coming out of the nozzle, effectively pulling the polymer out of the extruder. All polymers tested appear to have flowrates that are bounded by the freestream data, indicating that the extruder is able to deliver more material without the resistance generated between the nozzle and the moving platform. However, data in Figure 2 at low RPM is often higher for deposition than freestream, indicating that the platform velocity has a tendency to be greater than the velocity of the polymer exiting the nozzle during freestream extrusion, which serves to pull polymer at the nozzle exit and increase the flowrate during deposition.

The data in Figure 2 was used to fit a linear model of flow rate versus RPM, nozzle height, and table speed of the form

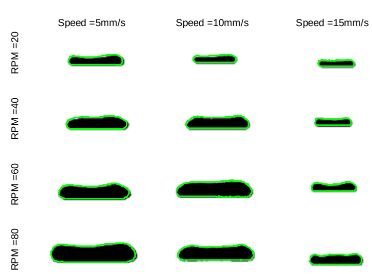
$$y = A_0 + A_1 R + A_2 H + A_3 S$$

where y is flow rate (in mm^3/s), R = RPM, H = nozzle speed (in mm), and S = table speed (in mm/s). Results of the linear regression for each of the materials appear in Table 2 with the calculated regression coefficient. Note that all flowrates increase with RPM with ABS having the highest slope. Also, flow rates for both the commercial copolyester and the 13% CF-ABS increase with nozzle height and table speed. However, ABS flow rates show an opposite trend. The regression coefficient for all models is relatively high, however, higher order terms may provide a better fit overall.

Table 2: Linear regression results for flow rate (in mm^3/s)

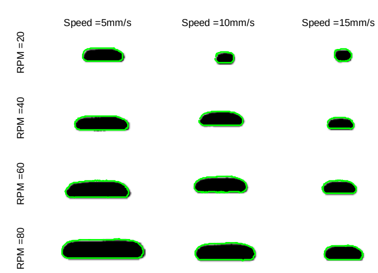
Material	A_0	A_1	A_2	A_3	R^2
commercial copolyester	184.54	11.64	0.87	7.09	0.825
ABS	721.71	20.42	-32.21	-13.03	0.879
13% CF ABS	145.10	18.29	8.37	25.93	0.868

General observations were taken of cross section shapes for each polymer across all parameters, in an effort to compare the shape effects of specific parameters across all polymers, and determine the sensitivity of shape to process parameters. Figure 3 shows plots of typical bead shapes at varying nozzle height, platform velocity, and extruder screw RPM.

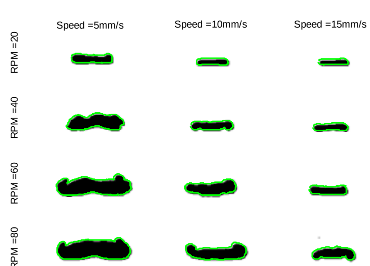


(a) nozzle height = 1.5 mm

(b) nozzle height = 3.25 mm



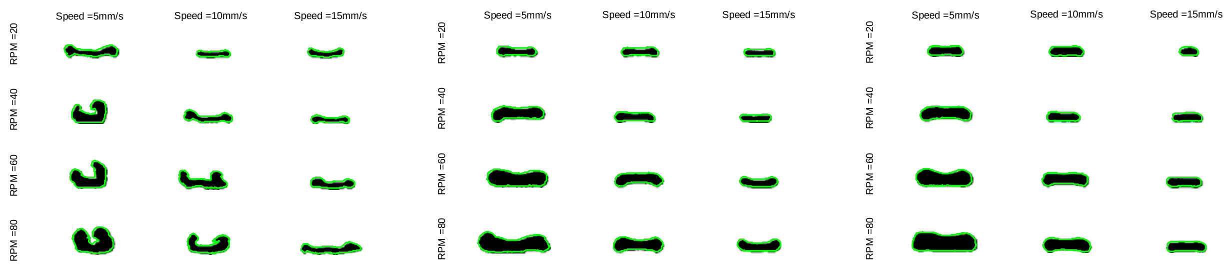
(c) nozzle height = 5.0 mm



(d) nozzle height = 1.5 mm

(e) nozzle height = 3.25 mm

(f) nozzle height = 5.0 mm



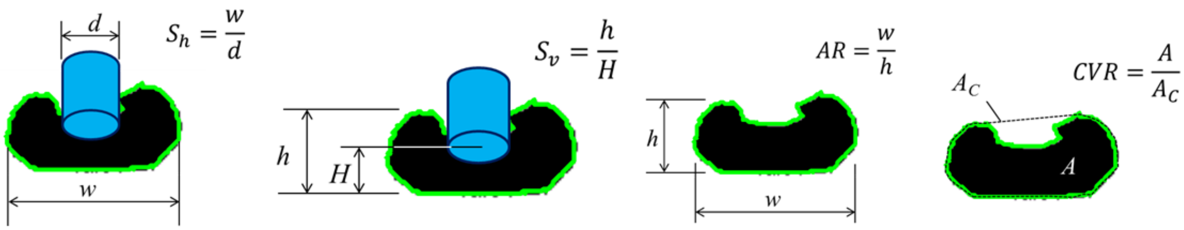
(g) nozzle height = 1.5 mm (h) nozzle height = 3.25 mm (i) nozzle height = 5.0 mm

Figure 3. Bead cross sections at nozzle heights of 1.5mm, 3.25mm, and 5 mm for commercial copolyester (a-c), Neat ABS (d-f), and 13% CF Filled ABS (g-i).

Of all three polymers considered here, the commercial copolyester appears to be the least sensitive to operational parameters since the general shape of the beads change little over the tested values of these parameters. The commercial copolyester beads are also the most regular in shape, while the ABS polymer blends have significant shape variation and surface defects across many input parameters. It is also interesting to observe the effect of short fiber inclusions in the general bead shape. The commercial copolyester and Neat ABS cross sections have greater aspect ratios than cross sections with carbon fiber inclusions. It is expected that internal stresses within the polymer during the extrusion process causes the beads with fiber inclusions to distort upward at the edges quite possibly due to the additional elastic response caused by the fiber inclusions. Cross sections also appear to be more highly irregular in the lower left sections of each plot as opposed to the upper right sections which appear more regular. This observation suggests that with increasing platform speed and decreasing screw RPM, parameter settings result in bead shapes that more suitable for FDM. Both RPM and platform speed effectively decrease the deposition rate of polymer onto the platform, yielding lower deposition rates and more rectangular bead shapes.

Surface roughness is another aspect that can be inferred from the cross section data. As shown in Figure 3, the ABS polymer blends have a higher degree of irregularity under most of the parameter settings. Alternatively, beads made of the commercial copolyester have smooth cross sections with little surface roughness, indicating a lower degree of inter layer bonding based on this parameter.

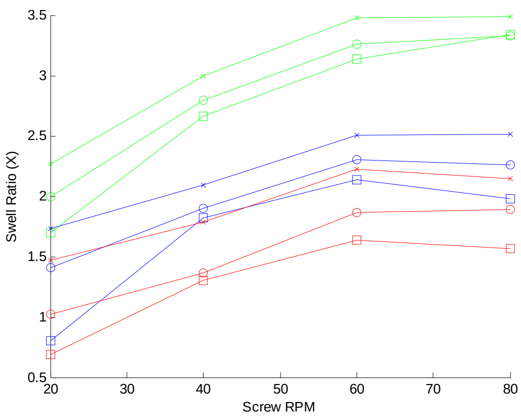
To better quantify the effect of processing parameters on bead geometry, we define the four shape metrics appearing in Figure 4. These are horizontal swell ratio, vertical swell ratio, aspect ratio, and convexity ratio. Quantifying horizontal swell is important since the acceptable distance between bead centers during the print is influenced by the actual width of the printed bead, not the nozzle diameter. The vertical aspect ratio is needed when determining the amount of height shift (i.e., z-direction adjustment) that is made when starting a new layer during printing. A large vertical swell may result in a collision between the print nozzle and previously deposited beads. The aspect ratio provides a measure of overall shape change between the melt that exits a round nozzle, and the bead as it is presented on the deposition platform. Finally, the convexity ratio provides a quantitative measure of the irregularity in shape that is seen in some of the printed beads, especially the carbon fiber filled beads. The legend for all curves appearing in Figures 5 through 8 is the same as that shown in Figure 2(a).

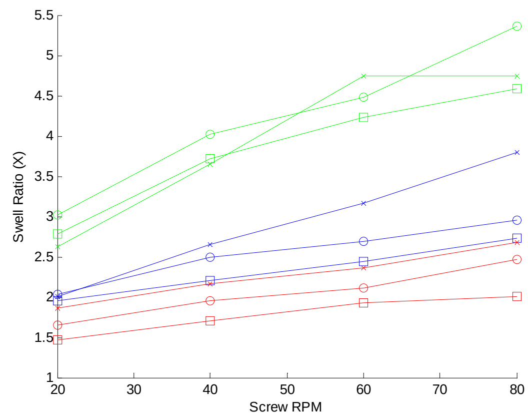


(a) (b) (c) (d)

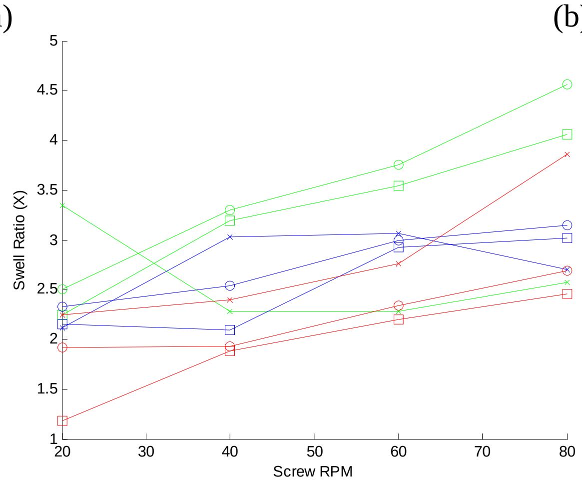
Figure 4: Bead geometry metrics (bead cross-X shown in black): Horizontal swell ratio S_h (a), Vertical swell ratio S_v (b), Aspect ratio AR (c), and Convexity ratio CVR (d).

Horizontal swell data in Figure 5 shows that S_h approaches values in excess of 5 for 80 RPM depositions with the lowest table speed. The unfilled ABS has the highest horizontal swell, and the commercial copolyester the smallest. All curves for the unfilled materials are relatively smooth, however, significant irregularities in S_h are seen for filled ABS, which can be expected given the cross section shape appearing in Figure 3 above. Overall the trends are that S_h increases with RPM, and decreases with platform speed and nozzle height, as expected. It is interesting to note that S_h tends to level off for the commercial copolyester at extruder speeds above 60 RPM.





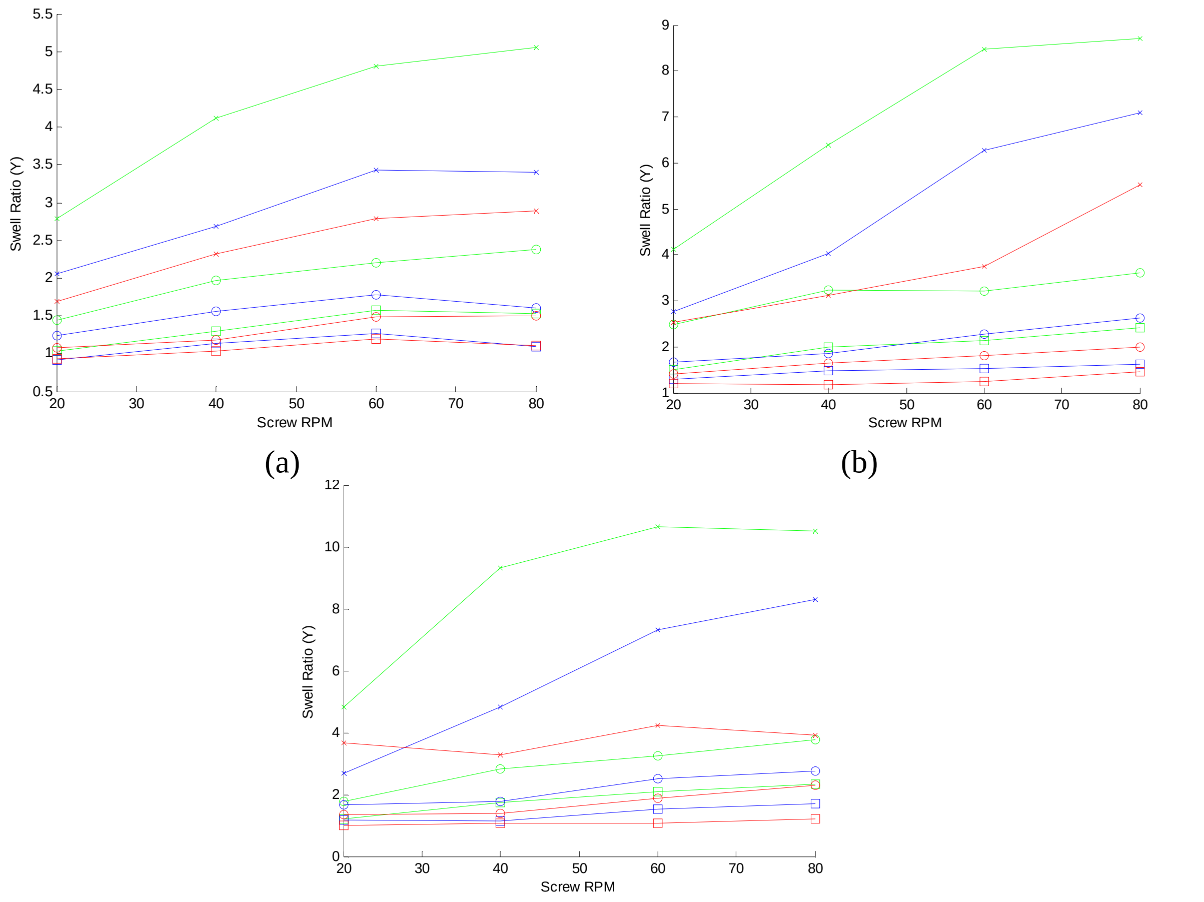
(a) (b)



(c)

Figure 5. Horizontal swell ratio S_h for the commercial copolyster (a), Neat ABS (b), and 13% CF Filled ABS (c). See Figure 2(a) for legend.

Plots in Figure 6 show that vertical swell ratio is rarely at or below unity, signifying that the print height would almost always be above the lower surface of the print nozzle. Of significance here is that S_v becomes quite large for high RPM and low table speed, and approaches a value of 10 for our CF ABS beads. Values of S_v appears to level off for extruder speeds above 60 RPM, and appears to be almost invariant with RPM for nozzle heights of 5mm. Otherwise, the general trends are similar to those for S_h, namely, S_v increases with RPM and decreases with platform speed and nozzle height.



(a) (b) (c)

Figure 6. Vertical swell ratio S_v for the commercial copolyster (a), Neat ABS (b), and 13% CF Filled ABS (c). See Figure 2(a) for legend.

Values of printed bead aspect ratio appear in Figure 7, plotted as functions of extruder RPM. The plots show that bead aspect ratio is relatively constant with RPM for the unfilled materials and also for most of the CF ABS setting. These results do, however, shows significant irregularities for carbon fiber filled ABS at low nozzle heights which may be expected given the irregular bead shapes that appear in Figure 3 (g) for 13% CF ABS. The results show that bead aspect ratio bead is influenced by nozzle height and platform speed. However, unlike results appearing above, AR increases with nozzle height and platform speed in some cases, and decreases in other.

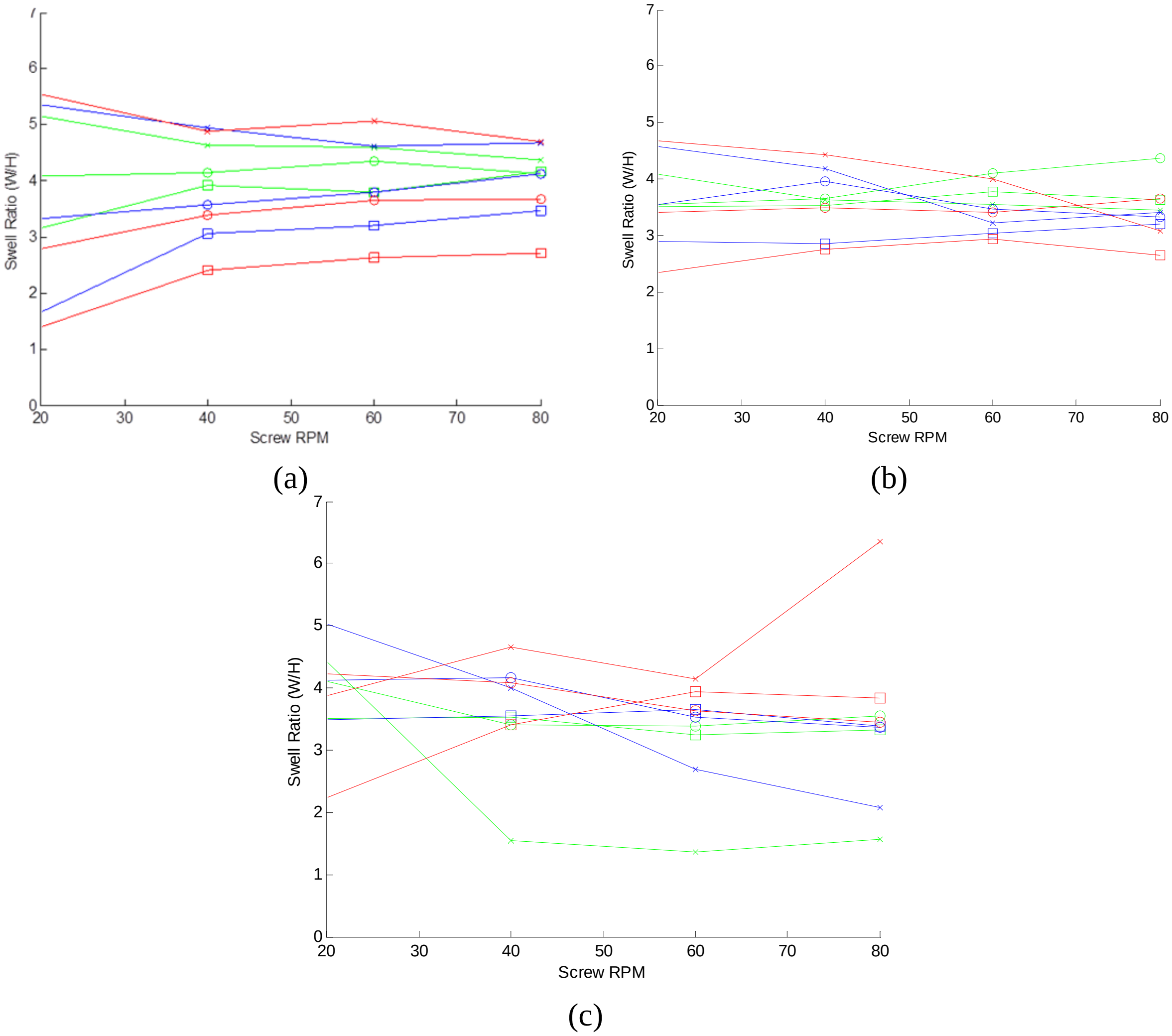
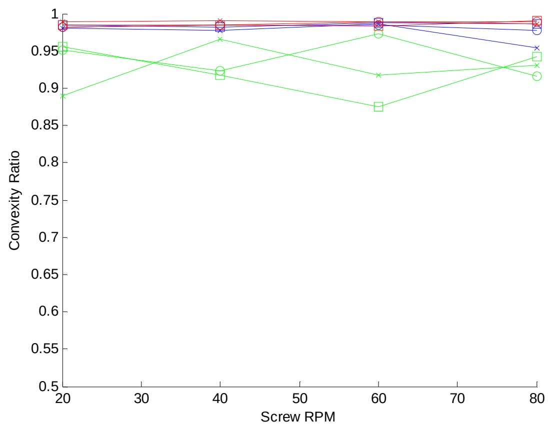
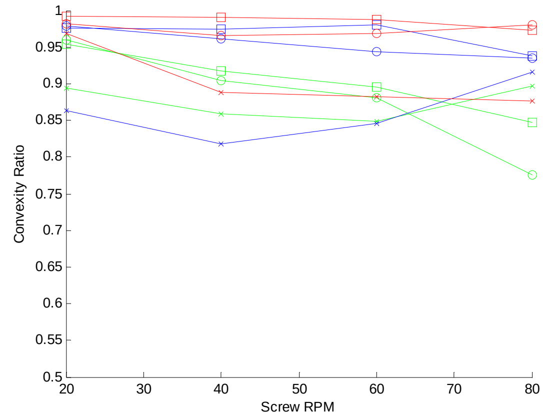


Figure 7. Aspect ratio (AR) for the commercial copolyester (a), Neat ABS (b), and 13% CF Filled ABS (c). See Figure 2(a) for legend.

Finally, this study considers convexity ratio appearing in Figure 8 as a metric to help identify beads which are less than optimal to the FDM process. Here we define a convexity ratio to assess the degree of irregularity in the shape of the bead as given in Figure 4(d). Convexity ratio is defined to compare the area of the existing bead cross section to the smallest convex shape which contains the entire cross section. A small convexity ratio indicates a very irregular bead cross section shape, typically with large amounts of material that has been squeezed out the sides of the nozzle-platform gap. Results in Figure 8 show that the convexity ratio approaches unity for all materials considered as the nozzle height and platform speed approach their largest values. It is seen that RPM has little effect on CVR, and that the irregular cross sectional geometries of CF ABS leads to low CVR approaching 0.65. The effect of nozzle height has a varying effect on CVR, however, CVR tends to increase with platform speed.



(a)



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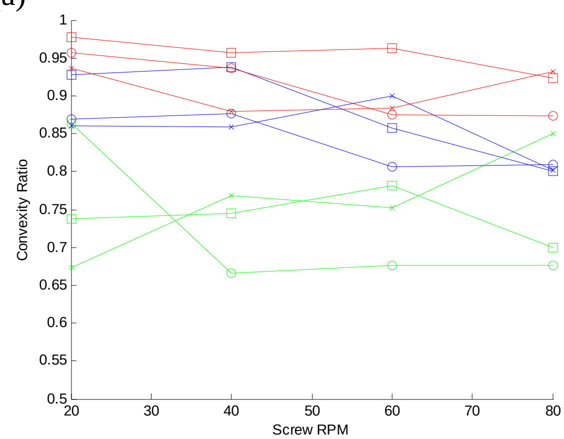

(c)

Figure 8. Convexity ratio (CVR) for the commercial copolyester (a), Neat ABS (b), and 13% CF Filled ABS (c). See Figure 2(a) for legend.

As previously mentioned, the shape of the commercial copolyester beads were the least sensitive to deposition settings, having the most regularly shaped cross sections of the four polymers tested. This is further supported by convexity ratio data in Figure 8, where a large portion of the commercial copolyester values are at or close to unity, while many convexity ratios for the ABS blends show values lower than one. By visual observation, the commercial copolyester bead shapes have very little concavity across all parameter settings, and show a convexity ratio of 0.9 or above. Neat ABS bead shapes tend to have convexity ratios above 0.9 as well, with the exceptions being beads printed at the lowest nozzle height (1.5mm) and the lowest platform velocity (5mm/s), of which the lowest nozzle height forces the polymer to travel further horizontally from the nozzle to satisfy the volumetric flowrate, and the lowest platform velocity increases the deposition volume and thus bead cross sectional area.

Conclusions and Future Work

A large scale fused deposition modeling system has been developed for the purpose of understanding the effect of various process settings on bead shape. The system uses a single screw extruder capable of producing up to 13pph HDPE, and an automated translation system with platform dimensions of 18”x18” with a horizontal platform velocity of up to 5 mm/s. Using this system, a range of parameter settings were evaluated to determine the effects of these parameters on the deposition bead geometry.

Flowrate was analyzed based on the cross sectional area of the beads and the platform velocity, which was compared with the freestream extrusion flowrate to examine the effect of pressure losses during the extrusion process, as well as other potential effects of the deposition process on extrusion. It was found that the freestream flowrate creates an upper bound on the flowrates at deposition parameters, with exceptions for the commercial copolyester due to output pulsing, and the ABS blends at low screw RPM's due to the platform creating an increase in pressure at the extrusion mouth from pulling the extrudate.

Cross section images from all polymers were visually examined to assess effects of the deposition process on cross sectional shape. It was seen that beads made of the commercial copolyester are only slightly affected by the parameters considered in this study while the ABS blends are highly affected, especially the carbon fiber filled ABS. Cross sections also become more regular in shape with decreasing screw RPM and decreasing platform speed, as both parameters serve to decrease the volume of polymer being deposited on the platform.

Vertical swell ratio was analyzed to assess the likelihood of having deposited beads that with elevated top surfaces. Values at and below unity indicate that the nozzle can pass back over areas it has already printed without concern for impacting the previously laid beads, while values above unity indicate that the nozzle cannot pass back over areas it has already printed in the current layer. The values shown for all polymers across all parameters are at and above unity, suggesting that the printing algorithm needs to account for an inability to pass back over previously printed areas, requiring greater print path complexity. The horizontal swell ratio is also in excess of one and tends to increase with RPM and decrease with nozzle height and platform speed. Shape aspect ratio and convexity ratio were used as a constraint to determine acceptable bead shapes, with convexity ratios much less than on suggesting a high degree of curvature and warping in the bead, and thus a bead shape which isn't optimal to the FDM process. Beads made of the commercial copolyester showed acceptable values of convexity across all parameters, while the ABS blends displayed several operation settings that wouldn't be acceptable for FDM. Specifically, the carbon fiber filled ABS beads showed a high degree of warping due to residual stresses in the fibers after deposition, with convexity ratio values dropping down as low as 0.65.

Results from this study suggest several areas of potential future work. A broader study with other common FDM materials would be beneficial for comparison, possibly including PLA and nylon. More widely spread values for platform velocity could be tested to examine the effects of high disparity between extrusion velocity and platform velocity, as well as changes in shape at higher and lower velocities. Finally, the vertical swell ratio showed values approaching unity as the nozzle height was increased, suggesting a potential optimum nozzle height greater than those examined.

Acknowledgements

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