Anisotropic mechanical performance of 3D printed polymers

Arthur Sebert*, Jared W. Nelson**, and Gregoire Bertacco*

*3D Matter, Brooklyn, NY arthur@my3dmatter.com
**SUNY New Paltz, Division of Engineering Programs, New Paltz, NY

ABSTRACT

As 3D printing continues to grow as a viable manufacturing process, quantification of the processing options and parameters will allow for better design and modeling of printed parts, or at least to clearly understand the trade-offs between the different options. To address this, a long-term, collaborative effort has been undertaken by the authors to accurately predict the properties of 3D-printed parts. 3D Matter has developed a model, Optimatter (www.optimatter.com), to fulfill this need by predicting the properties of printed parts depending on the printing technology, material and printing parameters used. This model is aimed at increasing the range of applications where 3D printing can be a viable manufacturing process. In order to get accurate property prediction, understanding the processing-performance relationship is needed. A comparison was made of the same materials, ABS and Nylon, printed with both a professional grade Fused Deposition Modeling (FDM) printer and a personal grade FDM printer. The result was three main findings: there is a decrease in performance along the Z-axis for both personal and professional printing; the properties along the X/Y-axes are very similar between the professional and the personal printers; and, the properties along the Z-axis are significantly better on the professional printer than on the personal printer. These results were expanded by using the OptiMatter platform further investigating the anisotropic properties of 3D printing processes. OptiMatter's data was used to complement the data points to comprehensively ascertain the difference between the different FDM manufacturing processes. It also added two new 3D printing processes: Selective Laser Sintering (SLS) and Stereolithography (SLA), showing that these processes were close to isotropic.

Keywords: mechanical performance, anisotropy, 3D printing, polymers, tensile testing

1 BACKGROUND

A comprehensive understanding of the impacts of process variations and methods of 3D printing with polymers has not been developed making it difficult to accurately design and consistently produce parts. Enhancing this understanding is a significant hurdle in the path for this technology to go from prototype-only to everyday use. To further this understanding, a study has been performed to clearly quantify the differences at the foundation of this technology by comparing the differences between printer grades using two common materials; acrylonitrile butadiene styrene (ABS) and nylon.

Even though there are few comparisons between traditional manufacturing methods such as injection molding and 3D printing, it is widely accepted that the mechanical properties are lower for printing due to the layer-by-layer process leaving gaps in the part and the thermal bonding being less effective. Several studies have investigated the effects and determined that print angle affects the mechanical properties [1-6]. Even fewer studies have been archived investigating the differences between printers, though it has been found that commercial grade printers performed more accurately [7-8].

2 MATERIALS & METHODS

The two materials used in this study were Stratasys ABSi and Stratasys Nylon-12 due their common use and availability. The materials were purchased as filament in sealed canisters for use in a Stratasys Fortus 400mc. Each material was not modified for use in either FDM process. A Stratasys Fortus 400mc was utilized as the professional grade FDM printer, while a MakerGear M2 was used as a representative personal FDM grade printer. The professional grade FDM 3D printer was defined as an expensive printer (>$10,000) that has a heated chamber, proprietary software with few degrees of freedom, and uses expensive, reliable, and precise components. On the other hand, the personal grade FDM 3D printer was defined as a low-cost printer ($500 - $5,000) that does not include a heated chamber and is made with fairly low-cost components. Based on these distinctions, the two printers chosen were representative matches for these two printer grades.

Printing in all cases was performed in two orientations with a linear (0°/90°) pattern at 100% infill with default print parameters with all printing parameters shown in Table 1. In all cases, tensile coupons were printed based on ASTM D638 (Figure 1, left). Specimen for impact testing were printed based on ISO 179. The two print orientations, horizontal and vertical, were utilized for comparison of layer adhesion (Figure 1, right). Horizontal coupons were printed such that tensile testing would elongate the 0° layer while the vertical prints were intended to directly test the bond between layers. The intent was similar for the impact testing.

In all cases at least 3 tensile specimens and 5 impact specimens were tested. Tensile testing was conducted with an Instron 1,000 Lb tension load cell, at a constant displacement rate of 5 mm/min. Elongation was measured with an extensometer. Un-notched Charpy impact testing was conducted with a 2J Hammer for all the ABSi specimens and the Nylon-12 specimens printed in Z. A 5J Hammer was used for XY Nylon-12 specimens.

	Professional FDM		Personal FDM	
	ABSi	Nylon 12	ABSi	Nylon 12
Printer / machine	Stratasys Fortus 400mc	Stratasys Fortus 400mc	Makergear M2	Makergear M2
Infill pattern	Linear (0°/90°)	Linear (0°/90°)	Linear (0°/90°)	Linear (0°/90°)
Number of shells, top/bottom layers	0	0	0	0
Layer height	0.25 mm	0.25 mm	0.2 mm	0.2 mm
Material Temperature	330°C	355°C	270°C	270°C
Ambient Temperature	85°C	120°C	25°C	25°C
Infill %	100%	100%	100%	100%
Printing Speed	N/A	N/A	30 mm/s	30 mm/s

Table 1: Processing parameters utilized for manufacture of all test specimen.

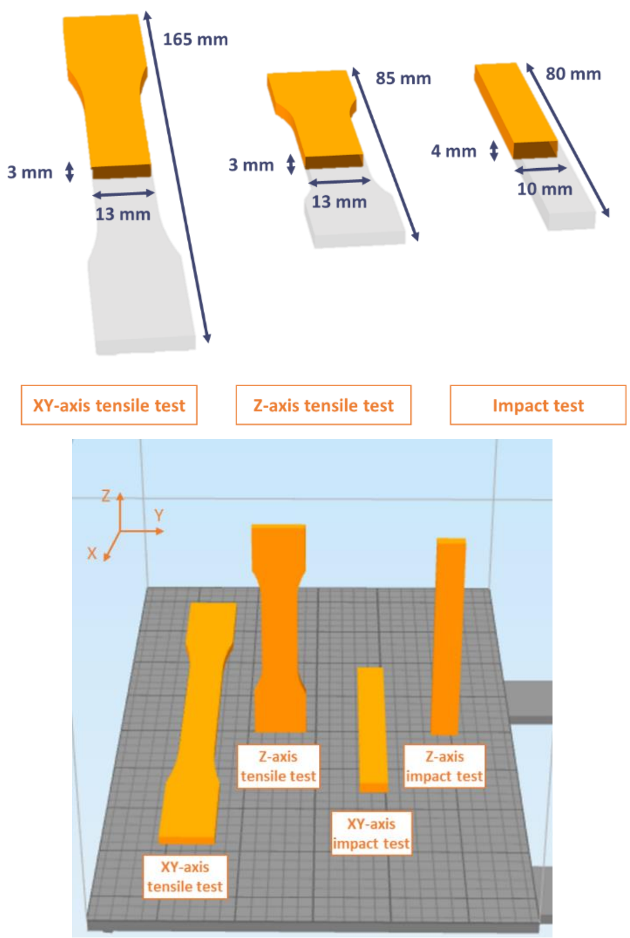

Figure 1: Coupons dimensions (top) and print orientation (bottom).

3 RESULTS

A representative ABSi tensile specimen from each process is shown below in Figure 2. Printed specimens below appear to have failed before a typical deformation occurred with brittle failure occurring between printed layers. It should be noted that the professional grade printer (top) appears to be more precise with clear distinction between layers compared to the personal grade printer (bottom).

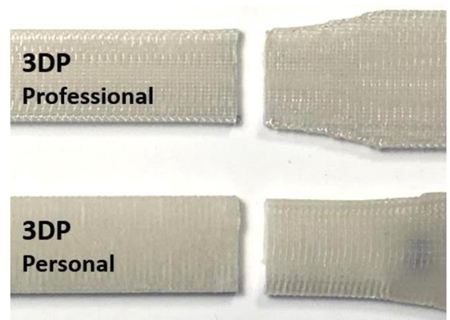

Figure 2: Representative quality and failure for specimen from each process.

Based on this testing, the results from these data collected indicate the following points:

- Performance decreases along the Z-axis for both personal and professional printing.
- Performance along the XY-axes are very similar between the personal and the professional grade printers.
- Performance along the Z-axis are significantly better on the professional printer than on the personal printer

To assess the anisotropy of 3D printed parts, the resulting data along the XY vs. Z axes were compared. A decrease in performance along the Z-axis compared to the XY-axes was observed and noted to be more pronounced for the personal printer than for the professional printer, likely due to the heated chamber and higher accuracy of the professional printer. The decrease in performance along the Z-axis is due to the layering process: along the XY-axes, the stress is applied on fibers extruded in one continuous process, while along the Z-axis, the stress is applied on layers that have been extruded at different times. Of note, the results indicate that 3D-printed ABSi and Nylon 12 both have a better performance along the Z direction than along the X/Y direction, meaning that FDM 3D-printed parts displayed an anisotropic behavior (Figure 3).

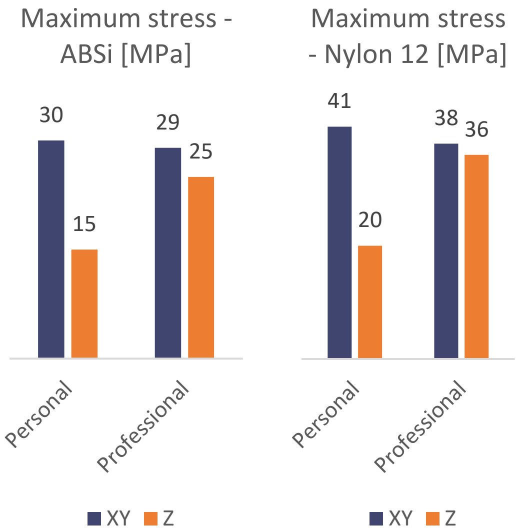

Figure 3: Comparison of test results for XY and Z print orientations of ABSi and Nylon 12 for personal and professional grade printers.

A similar comparison of the data was made to assess the variations between personal and professional printers (Figure 4). As indicated, the differences are small, less than 5%, between the personal and professional printers for maximum stress and yield stress. The differences are higher, between 15% and 30%, for elongation at break and impact resistance. Therefore, these data suggest that there is limited difference between the personal and professional printers along the XY-axes, for both ABSi and Nylon 12.

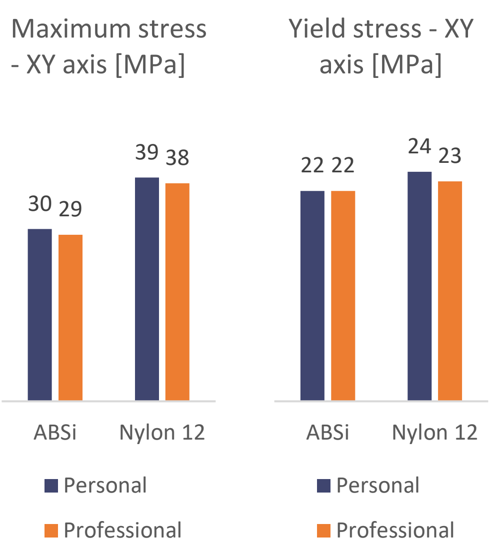

Figure 4: Comparison of XY orientation test results of personal and professional grade printers for ABSi and nylon.

When the Z axis is considered for 3D printing, the data indicate that the professional printer consistently results in higher performance than the personal printer (Figure 5). The performance increase along the Z-axis is likely linked to an improvement in adhesion between layers. There are several fundamental differences between a professional printer and a personal printer including that the professional printer has more expensive components, higher extrusion temperature and printing speed, as well as a heated chamber. Of these factors, it is most likely the heated chamber increased layer adhesion. The heated chamber keeps the entire part at a higher temperature, thus increasing the bonding between layers. When compared to the lack of a heated chamber on a personal printer where the part cools to the lower ambient temperature, the bond and part strength, yield point, elongation at break, and impact resistance all decrease. Given the smaller difference between the XY and Z printed parts, the parts printed on a professional printer are less anisotropic than those printed on a personal printer.

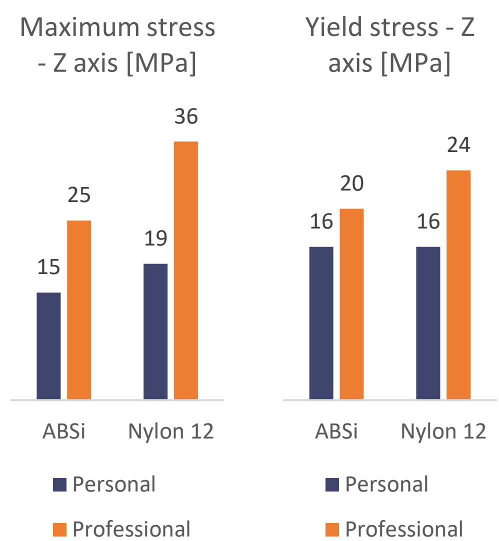

Figure 5: Comparison of Z orientation test results of personal and professional grade printers for ABSi and nylon.

4 APPLICATION

The conclusions of section 3. were drawn using only 2 materials. In 3D Matter's data platform OptiMatter[9], over 70 products were fully characterized as of March 2017, so the range of materials studied can be significantly expanded to confirm some of these conclusions. The testing methodology for the data recorded in OptiMatter is the same as the one described in section 2, so the data measured is comparable.

The following graph (Figure 6) combines the data from the section 3 and a selection of data from OptiMatter. It shows the mechanical performance measured for a large share of the materials present on the OptiMatter platform, with the two axes representing the maximum stress along the XY direction and along the Z direction. Each dot represents

TechConnect Briefs 2017, TechConnect.org, ISBN 978-0-9988782-1-8

the performance of one material. The dots are color-coded to show the forming technology used. An "isotropy" red line was also drawn where maximum stress along the XY direction is equal to maximum stress along the Z direction. Materials that are located on this line are isotropic with regard to maximum stress.

This graph confirms the following conclusions:

- FDM Personal is the most anisotropic manufacturing process tested. The light purple dots are generally much lower than the isotropy red line, meaning that the performance along the XY direction is much lower than the performance along the Z direction. Other processes are closer to the isotropy line.

- As we found in section 3, FDM Professional is less anisotropic than FDM Personal. Indeed, the dark purple dots are closer to the isotropy line than light purple dots.

- The new data from OptiMatter also shows that SLA and SLS present fairly isotropic properties:the orange and green dots are close to the red line. In three instances, for the SLA process, the orange dots are even slightly above the line, meaning that the performance along the Z direction was possibly marginally better than along the XY direction (although for the two closest to the line, it is probably just the margin of error).

- Injection molding is by definition isotropic, so the yellow dot is on the isotropy line.

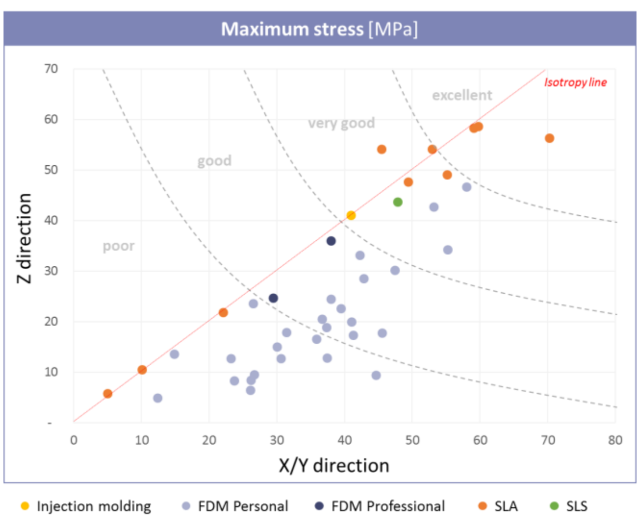

Figure 6 Matrix representing maximum stress along the XY direction and along the Z direction for a wide range of 3D printed polymers

Because each dot represent a different material, it is important to note that this analysis is based on a statistical observation rather than a comparative assessment like in section 3 of this paper. There seems to be enough data points for FDM Personal to show that it is on average a very anisotropic process, and enough data points for SLA to show that the isotropy is quite good. But FDM Professional only has two data points, and SLS only has one, meaning that further testing and data collection will be required to fully confirm the conclusions drawn in this section.

5 REFERENCES

1. Sood, A. K., Ohdar, R. K., & Mahapatra, S. S. (2010). Parametric appraisal of mechanical property of fused deposition modelling processed parts. *Materials & Design*, *31*(1), 287-295.
2. Dawoud, M., Taha, I., & Ebeid, S. J. (2016). Mechanical behaviour of ABS: An experimental study using FDM and injection moulding techniques. *Journal of Manufacturing Processes*, *21*, 39-45.
3. Ahn, S. H., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid prototyping journal*, *8*(4), 248-257.
4. Montero, M., Roundy, S., Odell, D., Ahn, S. H., & Wright, P. K. (2001). Material characterization of fused deposition modeling (FDM) ABS by designed experiments. *Society of Manufacturing Engineers*, *10*(13552540210441166).
5. Weng, Z., Wang, J., Senthil, T., & Wu, L. (2016). Mechanical and thermal properties of ABS/montmorillonite nanocomposites for fused deposition modeling 3D printing. *Materials & Design*, *102*, 276-283.
6. Ziemian, S., Okwara, M., & Ziemian, C. W. (2015). Tensile and fatigue behavior of layered acrylonitrile butadiene styrene. *Rapid Prototyping Journal*, *21*(3), 270-278.
7. M. Johnson, W., Rowell, M., Deason, B., & Eubanks, M. (2014). Comparative evaluation of an open-source FDM system. *Rapid Prototyping Journal*, *20*(3), 205-214.
8. Roberson, D. A., Espalin, D., & Wicker, R. B. (2013). 3D printer selection: A decision-making evaluation and ranking model. *Virtual and Physical Prototyping*, *8*(3), 201-212.
9. 3D Matter (2017). *OptiMatter*. Brooklyn, NY.