STUDY OF INFILL PRINT PARAMETERS ON MECHANICAL STRENGTH AND PRODUCTION COST-TIME OF 3D PRINTED ABS PARTS

Liseli Baich* and Guha Manogharan*

*Department of Mechanical and Industrial Engineering, Youngstown State University,

Youngstown, OH 44555

REVIEWED

Abstract

The ever-growing adoption of Additive Manufacturing (AM) can be attributed to lowering prices of entry-level extrusion-based 3D Printers. It has enabled using AM for mainstream DIY, STEM education, prototypes and often, to produce custom complex commercial products. With the growing number of available printers and newer materials, the influence of print parameters specifically infill patterns on the mechanical strength and print costs need to be investigated. This study presents the correlation of infill pattern selection and several mechanical properties along with final part cost and production time. Infill with varying design parameters are analyzed with respect to mechanical properties determined using ASTM standards, fabrication cost and time. Relevant applications are presented for all the varied infill designs. Findings from this study will help formulate criteria for relevant economically sound infill design pattern for real world applications.

Keywords: Additive Manufacturing, Material Extrusion, Fused Deposition Modeling, Mechanical Strength, Infill Print Parameters and Cost Analysis,

Introduction

Additive manufacturing uses a 3D CAD (Computer Aided Design) model of the desired part by selectively joining materials layer by layer [1]. This ‘Solid Freeform’ approach to fabricate parts provides unique advantages such as lack of fixtures/jigs, part-independent build set-up, ability to produce multiple designs within a single build among others [2]. The ability to customize part designs, materials, and colors including multi-colored part fabrication provides an ever-growing possibility for limitless real world applications.

Among the different categories of ASTM (American Society of Testing and Materials)-defined AM (noted below), material extrusion has gained tremendous popularity in a range of applications ranging from DIY projects, STEM education, prototype fabrication and actual part production [3-5]. This method is popularly referred to as Fused Deposition Modeling (FDM) and is relatively cheaper, easier to set-up with lower consumable and maintenance cost [6]. Material Extrusion is an “AM process in which material is selectively dispensed through a nozzle or orifice” [7]. Since AM is relatively more affordable from its earlier days [8], STEM programs throughout the nation are adopting additive manufacturing in their curriculums at a much lower cost. The focus of this study is to develop the framework related to material extrusion AM; specifically ‘infill pattern’ which is an integral and often an overlooked aspect with respect to its resulting mechanical properties and cost-production time requirements. Relevant background for this motivation and under-taken methodology are presented in this work. Analyses of the experimental results obtained by conducting tensile, compression, and bending tests are compared to material consumption and print costs.

Background

According to ASTM F2792, AM processes can be categorized into seven categories: vat photo-polymerization, material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination and directed energy deposition [7].

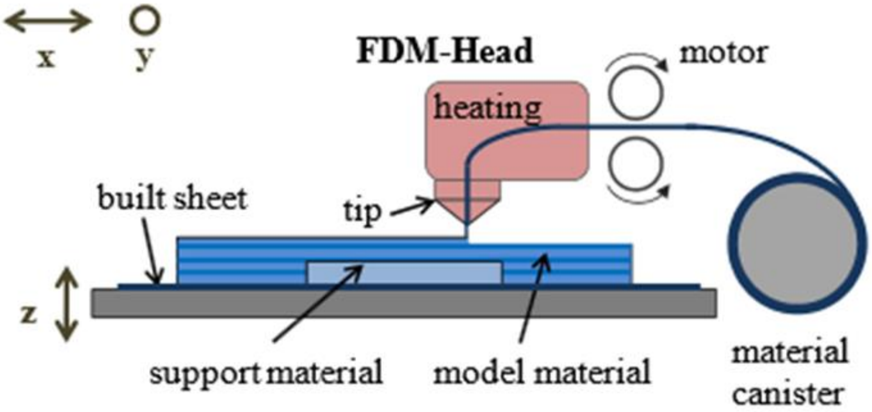


Figure 1: Material Extrusion Process [9]

In the case of material extrusion as shown in Figure 1, there are several process parameters that influence the final part strength, quality, cost and production time including (but not limited to): (1) Material and support selection [10] , (2) Part design [11], (3) Layer thickness [12 and 13], (4) Print design (wall thickness, **infill pattern**) [12 and 14], (5) Print conditions (uniformity of extruder and/or build-bed temperature) [11], and (6) Presence of re-enforcing material (e.g. carbon fibers).

With the ever-increasing interests in using 3D printing and growth of open-access CAD and STL repositories such as Thingiverse and PinShape to name a few; it is important to identify which infill patterns and densities will provide ideal strength for different applications. This is of great significance because in material extrusion AM, the CAD model (as an STL file being a water-tight knit 3D surface facets) **does not have any information on the infill pattern**. Most often, the in-fill pattern is based on the 'default' settings of the 3D printing manufacturers and/or open-source tool-path generating software. The CAD model also contains no information concerning loading during usage, which can vary widely in different parts and therefore require different material properties. For example, the mechanical properties of a the snap buckle as shown in Figure 2 would be mostly exposed to a tensile load when compared to the laptop wedge shown in Figure 3 and the mounting plate shown in Figure 4 where primary loading would be compressive and bending, respectively.

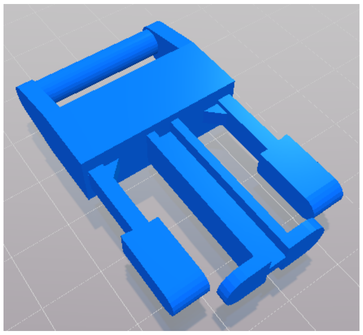


Figure 2: Buckle [15]

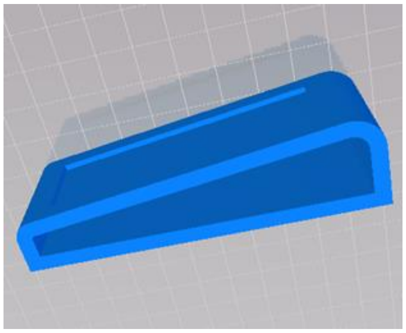


Figure 3: Laptop wedge [16]

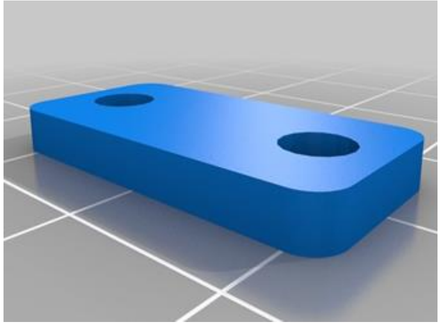


Figure 4: Mounting Plate [17]

The ability to change infill dimensions and layer thicknesses can significantly impact the mechanical properties [12] (if selected irrespective of real world applications), material cost and production time taken to create a product. Several open-access software are available including Slic3r, Repetier, and Simplify3D for most entry-level 3D printers to generate a toolpath with varying levels of user control. On the other hand, Stratasys Fortus 3D printer is a production grade printer which uses Insight® with relatively lesser control than entry level printers, in infill pattern design but with superior accuracy and quality [18]. With the ability for decision freedom along with the other material extrusion parameters noted above, infill print parameters will affect the mechanical performance and production economics of a material extrusion part. Specifically, contours is defined as the variable to change the thickness of the perimeter walls in the print at each layer. This is done by adding to the number of walls or changing the thickness of each contour. Another infill parameter that can be changed is the spacing between the contour and the raster, the infill pattern, and the spacing between each raster line as shown in Figure 5. In this study the main focus is to evaluate several infill patterns against the benchmark of a solid infill pattern. In future work the custom parameters with respect to the part geometry and loading conditions can be evaluated using the proposed framework.

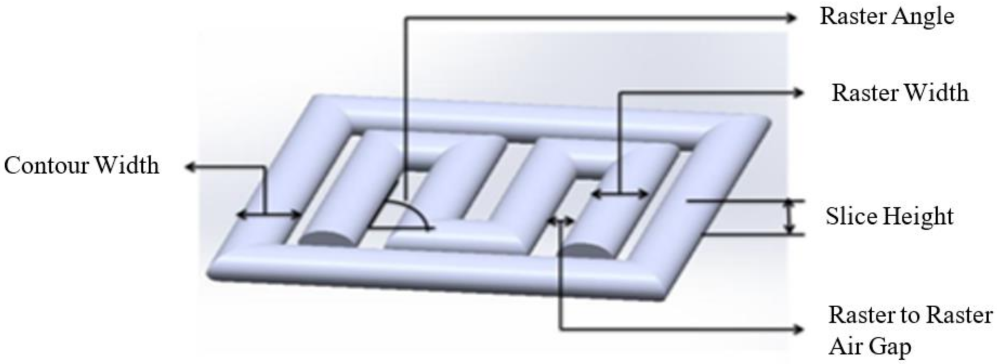


Figure 5: FDM Build Parameters [7]

The current literature has analyzed the correlation between print parameters, specifically infill pattern along with its interaction with layer thickness and print performance. A study of the effects of filament thickness, print orientation, and raster angle indicated that thicker filament provides better mechanical properties if printed in the x and z direction and thinner filament is ideal for prints in the y direction [9]. Another study compared mechanical properties when air gap, cap thickness, and wall thickness were varied. The results showed that cap thickness is the most important parameter in flexure tests, and that as the air gap increases so does strength to mass and modulus to mass ratios [14]. It was also determined that wall thickness has no clear effect on the strength. Another study compared the raster width, contour width, and air gap at different raster angles [19]. The results stated that by decreasing the contour width and raster width the ultimate tensile strength (UTS) increases. However, the sample with the lower contour and raster width and the negative air gap resulted in the highest UTS for all samples. Another approach compared the compressive strength in samples with lattice structures as infills and the default infill densities [20]. The results overwhelmingly favored the lattice structure infill. Since the honeycomb lattice structure was the strongest. Its mechanical properties were compared to sparse and double dense values. The yield stress for the honeycomb was 217% and 253% higher than the double dense and sparse, respectively, and the compressive modulus of the honeycomb structure was 286% and 579% stronger than the double dense and sparse, respectively. The review of infill effect research clearly shows that there is still a need for studies that compare infill parameters and mechanical properties of tensile, compression, and bending loads for ABSplus material, and the correlation of the time it takes to print each sample along with a cost analysis.

The work presented in this paper will specifically study the relationship between infill design parameters, mechanical strength and production economics. It should be noted that although this work used a production grade printer and partial infill parameter combinations, the proposed methodology can be adapted and extrapolated to other entry-level material extrusion systems and infill parameters. This work primarily aims to develop a comprehensive framework for ‘print design-mechanical properties-cost estimation’ based on real-world applications. This understanding will aid in the analysis of the correlation between cost and time with infill design attributes and mechanical properties. For instance, one infill design could be more appropriate for tensile load but not the ideal design if the part is subjected to bending load. The study will provide companies with valuable information on production time, economics including material consumption with respect to final mechanical properties desired in the produced part.

Methodology

The material extrusion machine used in this study is the Stratasys Fortus 200mc using ABSplus-P430 plastic, a type of Acrylonitrile Butadiene Styrene (ABS) with a T14 nozzle tip and a layer thickness of 0.254 mm (0.01 in). Print parameters that were varied, as shown in Figure 6, using the Insight® software include D1 (low), D2 (high), D3 (double dense), and D4 (solid) densities.

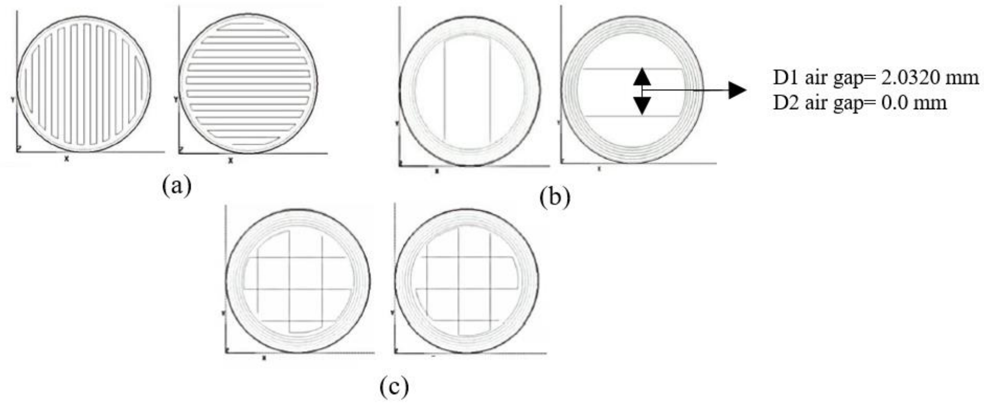


Figure 6: FDM Build Styles (a) solid- build (D4), (b) sparse-build (D1 and D2), (c) sparse – double dense build (D3) [14]

In order to evaluate the print performance, three trials per infill design are produced with determination of material consumption ($4.28/in^3) and production time ($30/hr). Since the set-up and part retrieval times are the same, they have not been included. The material consumption cost was determined using a standard spool price of $260 and a volume of 56.3 in^3. The samples were designed using Siemens NX and Solidworks software based on the parameters stated in the appropriate ASTM standards. Specifically, the samples had nominal dimensions of: (1) Tensile Type I, w=13mm, t=3.2mm, Gage Length=57mm, Overall Length=165mm; (2) Compression w= 12.7 by t= 25.4 by Length= 12.7 mm; and (3) Bending w= 12.7 by t= 3.2 by Length= 127 mm. The mechanical testing was conducted using Instron Model 5967 mechanical equipment with a 30kN Load Capacity capable of 0.25% accuracy over the entire range while following ASTM Tensile D638, Compression D695, and Flexural D790 test requirements. Test speeds varied for each test: Tensile- 5 mm/min, Compression- 1.3 mm/min, and Flexural- 0.5 mm/min were used to conduct the tests [21-23]. The samples were measured before testing using a digital caliper with an accuracy of ± .01 mm to record the specimen dimensions.

Results and Analysis

		Tensile		**Compression**		**Bending**	
Density	**Symbol**	**Print Time (min)**	**Volume (in^3)**	**Print Time (min)**	**Volume (in^3)**	**Print Time (min)**	**Volume (in^3)**
Low	**D1**	**24**	**0.42**	**16**	**0.15**	**17**	**0.27**
High	**D2**	**25**	**0.49**	**17**	**0.2**	**18**	**0.3**
Double Dense	**D3**	**26**	**0.45**	**19**	**0.18**	**18**	**0.3**
Solid	**D4**	**25**	**0.55**	**18**	**0.26**	**17**	**0.34**

Table 1: Print Time and Material Consumption

Table 1 shows the print time (minutes) and material consumption (in^3) for samples produced with different in-fill pattern. It should be noted that double dense in-fill pattern (D3) took the longest time to print for each test but did not use the most amount of material. This can be explained by the additional time (non-depositing) that is required for solid (D4) and high dense (D2) and double dense (D3) as shown in Figure 7. However, there appears to be a break-through point, where low (D1) is not affected by the additional time in motion without depositing. Figure 8 shows the total cost of each sample and again shows that double dense (D3) is the most expensive overall.

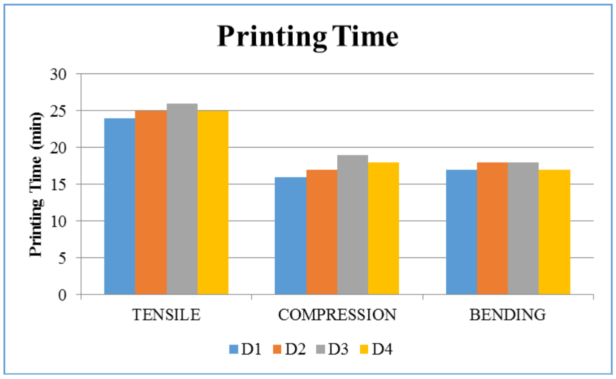


Figure 7: Printing Time (min) vs. Infill Designs

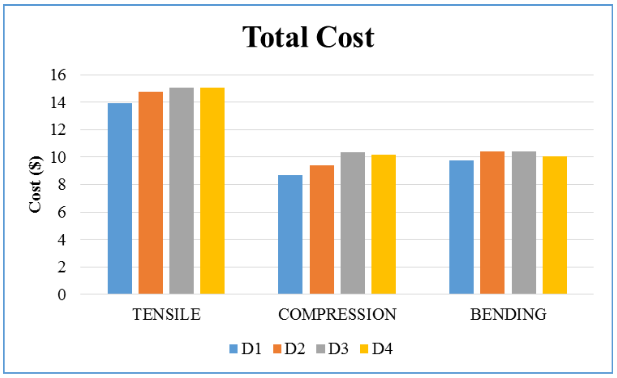


Figure 8: Total Cost vs. Density

Tensile:

Figure 9 and 10 show the ultimate tensile strength (UTS) and modulus (E) of the tensile specimens, respectively in Mega-Pascal (MPa). The plot shows that the solid samples had the highest tensile strength as expected. It is interesting to note that the low and high density samples had similar strength but the low density infill samples require the least amount of material and time to print. The double dense and solid samples were also close in strength. This shows that if the printed part is to be subject to tensile load, double dense is not a desired in-fill design. This is counter intuitive in terms of additional material for resulting in increased strength.

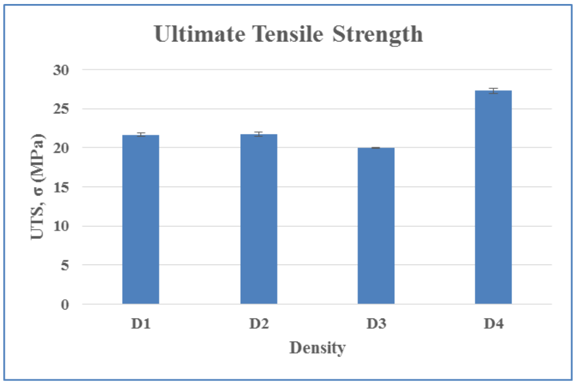


Figure 9: UTS vs Density

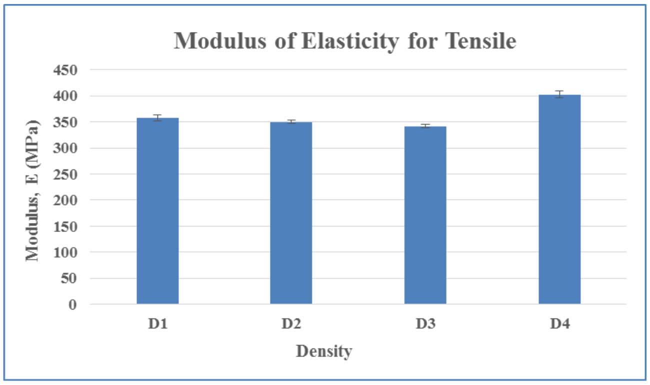
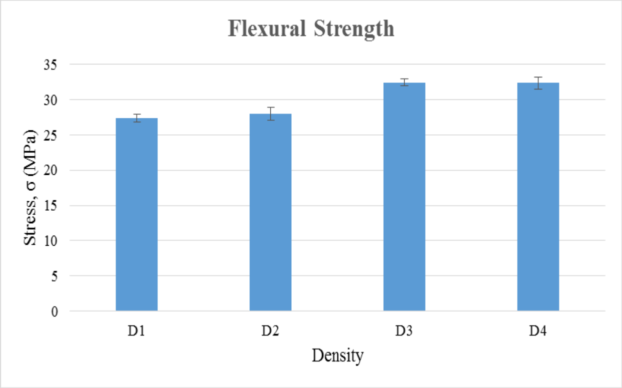


Figure 10: Modulus of Elasticity vs Density

Three-Point Bending:

Figures 11 and 12 show the flexural strength and flexural modulus of the three point bending samples. It can be seen that change in infill pattern did not drastically change the flexural strength (unlike tensile tests). It is also noted that the flexural modulus follows a similar trend as the flexural strength.



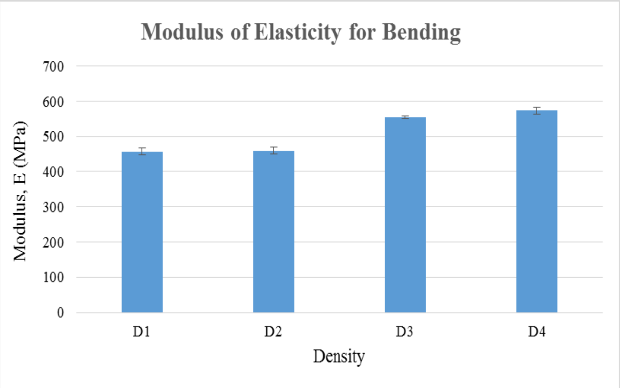
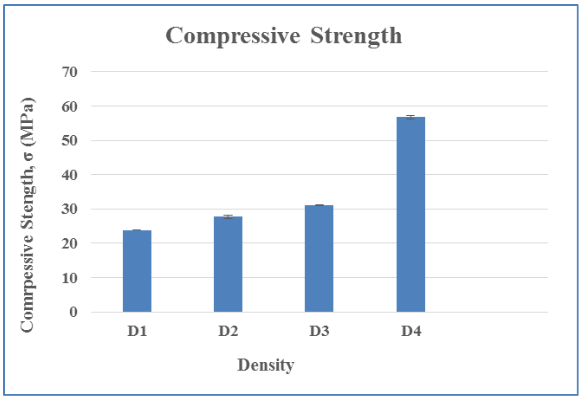


Figure 11: Flexural Strength vs Density

Figure 12: Modulus of Elasticity vs Density

Compression:

Figure 13 and 14 shows the Compressive Strength and Modulus of Elasticity of the compression samples tested. Figure 11 shows that the compressive strength was the highest for solid , as expected. Figure 12 shows the results of the modulus of elasticity with higher variability and low density and solid has the lowest and highest values respectively, which was expected.



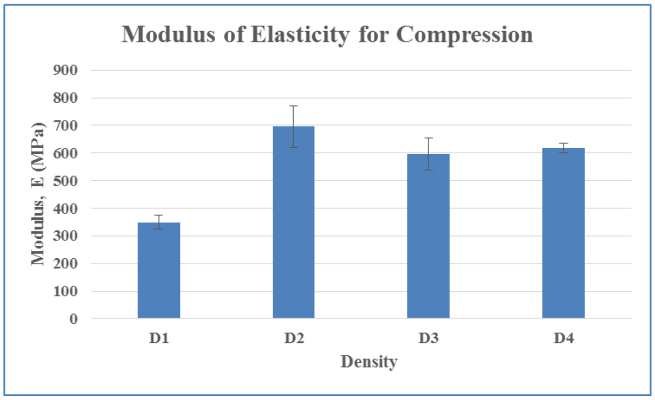


Figure 13: Compressive Strength vs Density

Figure 14: Modulus of Elasticity vs Density

Cost Analysis:

Figure 15 shows the reduction in cost (%) and the strengths for tensile, bending and compression (%) when compared to solid in-fill (D4). Higher reduction in cost (%) means greater cost savings (with respect to D4) and higher reduction in mechanical strength (%) means greater loss in mechanical strength (with respect to D4). For instance with the tensile test samples, there was no loss in strength between D1 and D2 but D1 provides a larger cost savings. In the case of bending, it is noted that there was very little change in strength again between D1 and D2 while D1 provides the largest cost savings. It is also observed that the change in strength increases in D3 while the cost savings stay relatively the same. In the case of compression, the reduction in strength steadily increases while the cost savings between D2 and D3 stay the same, which means that there is no change in cost between D2 and D3 but there is improved strength.

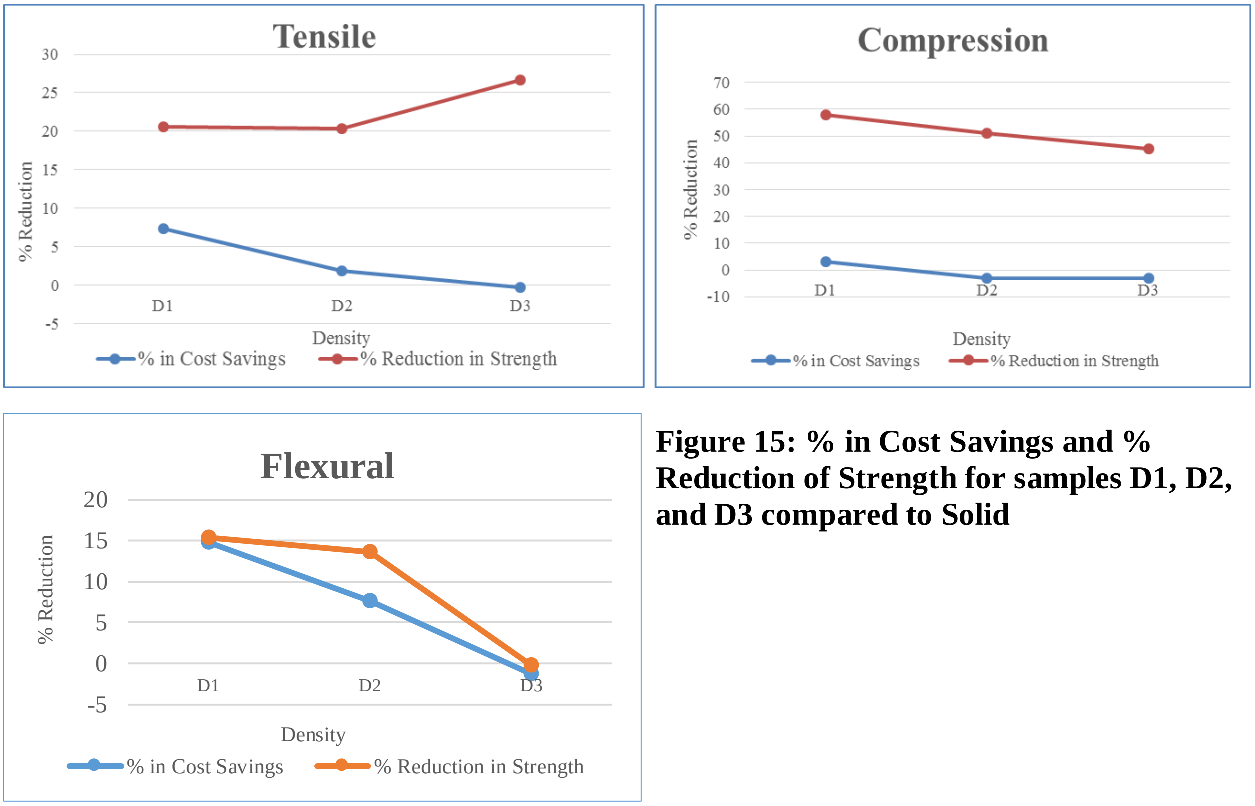


Figure 15: % in Cost Savings and % Reduction of Strength for samples D1, D2, and D3 compared to Solid

Conclusion

Real world applications of AM are ever-growing because of the ability to customize designs, material and color selection. With the growing number of CAD repositories in websites like Thingiverse and PinShape, access to STL files for printing is even easier. However, the model does not take into account the in-fill pattern. The focus of this study was to study the mechanical properties in correlation to the production time and the material cost. The results revealed that for tensile, D1 could be used instead of D2 and money is saved but strength is not sacrificed. For bending, D1 is ideal because the strength remains similar to D2 but cost is less. D3 provides a much larger change in strength but costs more due to additional non-depositing time, if a higher strength is needed. The results for the compression samples explain that the strength goes up steadily but the cost stays the same between D2 and D3 so the ideal option for parts exposed to compression loads, is D3. From this study, it was found that printing solid infill is beneficial in the case of bending and compression samples when compared to non-solid in-fill patterns. Additional analysis on ‘custom’ infill pattern with respect to mechanical loading (similar to directional grain growth in metal parts) and incorporating material vs. printing duration would be useful. Future work will include the use of finite element analysis (FEA) to predict which how forces will affect customized parts. The overall goal is to customize infill design parameters for printing parts based on loading conditions which provide the largest cost-efficiency along with desired mechanical properties.

References

[1] *Additive Manufacturing*. N.p.: Materialise, 17 June 2015. <http://www.materialise.com/glossary/additive-manufacturing>.

[2] Guo, N., and M. C. Leu. *Additive Manufacturing: technology, applications and research needs*. Frontiers of Mechanical Engineering. pp.215-243.

[3] Bak, D. *Rapid prototyping or rapid production? 3D printing processes move industry towards the latter*, Rapid Prototyping Journal, 2003. pp. 340-345

[4] Conner, B. P., G. P. Manogharan, A. N. Martof, L. M. Rodomsky, C. M. Rodomsky, D. C. Jordan, and J. W. Limperos. *Making Sense of 3-D Printing: Creating a Map of Additive Manufacturing Products and Services*. Elsevier Editorial System(tm) for Additive Manufacturing ADDMA-D-14-00014R1, pp. 1-47.

[5] Petrick, I.J., T.W. Simpson: *3D printing disrupts manufacturing: how economies of one create new rules of competition*. Res Technol Manage, 2013, pp. 12–16

[6] *Fused Deposition Modeling*. Solid Concepts, Web. pp.1-8. 16 June 2015. <https://www.solidconcepts.com/content/pdfs/brochures/fused-deposition-modeling-fdm-brochure.pdf>.

[7] ASTM F2792-12a, *Standard Terminology for Additive Manufacturing Technologies*, ASTM International, West Conshohocken, PA, 2012, www.astm.org

[8] Jauhar, S., K. M. Asthankar, and A.M. Kuthe. *Cost benefit analysis of Rapid Manufacturing in Automotive Industries*. Advances in Mechanical Engineering and its Applications (AMEA) 181. 2012, pp. 2167-6380 Copyright © World Science Publisher, United States

[9] Bagsik, A., and V. Sch¨oppner, *Mechanical properties of fused deposition modeling parts manufactured with Ultem*9085*. In Proceedings of the 69th Annual Technical Conference of the Society of Plastics Engineers (ANTEC ’11), pp. 1294–1298, Boston, MA, May 2011.

[10] Fischer, Fred. *Thermoplastics: The Best Choice for 3D Printing*. Stratasys, pp. 1-5. Web. 14 June 2015. <http://www.appliancedesign.com/ext/resources/AM/Home/Files/PDFs/themoplastics.pdf>

[11] Kumar, G.P., and S.P. Regalla. *DOE Based Parametric Study of Volumetric Change of FDM Parts*. Procedia Materials Science 6. 2014. pp. 354-360.

[12] Sood, A. K., R. K. Ohdar, and S. S. Mahapatra. *Grey Taguchi Method for Improving Dimensional Accuracy of FDM Process*. AIMS International Conference on Value- based Management, 2010. pp. 1-6.

[13] Boschetto, A., and L. Bottini. *Accuracy Prediction in Fused Deposition Modeling*, pp. 1-16. 2014.

[14] Iyibilgin, O., M. C. Leu, G. Taylor, H. Li, and K. Chandrashekhara. *Investigation of Sparse-Build Rapid Tooling by Fused Deposition Modeling*. pp. 1-15 in Solid Fabrication Symposium, Austin, TX, 2014.

[15] *Buckle Replacement for Ortlieb Bike Panniers*: Makerbot Thingiverse, 2015. Web. 14 July 2015. <http://www.thingiverse.com/thing:924975/#files>.

[16] *Laptop Wedge*: Makerbot Thingiverse, 2015. Web. 14 July 2015. <http://www.thingiverse.com/thing:915525>.

[17] *Shims, Mounting Plates, and Standoffs for 0824 Makeblock Beams*: Makerbot Thingiverse, 2015. Web. 14 July 2015. <http://www.thingiverse.com/thing:737972>.

[18] Pei, E., R. I. Campbell, D. Beer. *Entry-level RP machines: How well can they cope with geometric complexity?*, Assembly Automation, 2011. pp.153 – 160.

[19] Hossain, M. S., J. Ramos, D. Espalin, M. Perez and R. Wicker, *Improving tensile mechanical properties of FDM-manufactured specimens via modifying build parameters*, in Solid Fabrication Symposium, Austin, TX, 2013.

[20] Iyibilgin, O., C. Yigit, and M. C. Leu. *Experimental investigation of different cellular lattice structures manufactured by fused deposition modeling*. Proceedings of Solid Freeform Fabrication Symposium, Austin, TX, 2013, pp. 895-907.

[21] ASTM D638-14, *Standard Test Method for Tensile Properties of Plastics*, ASTM International, West Conshohocken, PA, 2014, www.astm.org

[22] ASTM D695-10, *Standard Test Method for Compressive Properties of Rigid Plastics*, ASTM International, West Conshohocken, PA, 2010, www.astm.org

[23] ASTM D790-10, *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*, ASTM International, West Conshohocken, PA, 2010, www.astm.org