Tensile strength of commercial polymer materials for fused filament fabrication 3D printing

Nagendra Tanikella, Ben Wittbrodt, Joshua Pearce

Preprint: Nagendra G. Tanikella, Ben Wittbrodt and Joshua M. Pearce. Tensile Strength of Commercial Polymer Materials for Fused Filament Fabrication 3-D Printing. *Additive Manufacturing* 15: pp. 40–47 (2017). DOI: 10.1016/j.addma.2017.03.005

Tensile Strength of Commercial Polymer Materials for Fused Filament Fabrication 3D Printing

Nagendra G. Tanikella[1], Ben Wittbrodt[2] and Joshua M. Pearce[2,3,*]

1. Department of Mechanical Engineering–Engineering Mechanics,Michigan Technological University, Houghton, MI 49931, USA
2. Department of Materials Science & Engineering, Michigan Technological University, Houghton, MI 49931, USA
3. Department of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI 49931, USA

*Corresponding author: Michigan Technological University, 601 M&M Building, 1400 Townsend Drive, Houghton, MI 49931-1295 (pearce@mtu.edu) ph: 906-487-1466

Abstract

3D printing functional parts with known mechanical properties is challenging using variable open source 3D printers. This study investigates the mechanical properties of 3D printed parts using a commercial open-source 3D printer for a wide range of materials. The samples are tested for tensile strength following ASTM D638. The results are presented and conclusions are drawn about the mechanical properties of various fused filament fabrication materials. The study demonstrates that the tensile strength of a 3D printed specimen depends largely on the mass of the specimen, for all materials. Thus, to solve the challenge of unknown print quality on mechanical properties of a 3D printed part a two step process is proposed, which has a reasonably high expectation that a part will have tensile strengths described in this study for a given material. First, the exterior of the print is inspected visually for sub-optimal layers. Then, to determine if there has been under-extrusion in the interior, the mass of the sample is measured. This mass is compared to the theoretical value using densities for the material and the volume of the object. This two step process provides a means to assist low-cost open-source 3D printers expand the range of object production to functional parts.

Keywords: Mechanical Properties; Distributed Manufacturing; RepRap; Polymers; 3D Printing

1. Introduction:

Due to the open-source release of the RepRap (self-Replicating Rapid prototyper) [1-3] there was a distinct rise in popularity of 3D printing at the small scale [4]. RepRap 3D printers fabricate parts using fused filament fabrication (FFF) (material extrusion by ASTM Standard F2792-12a) and various RepRap printer designs make up the majority of 3D printers in use now [5]. Decentralized manufacturing is possible with at-home 3D printing both in the developing [6] and developed countries [7]. Previous studies have shown that such manufacturing not only allows for a lower cost of goods for the consumer [8], but a lower impact on the environment as well [9,10]. With users from various 3D printing repositories (e.g. Youmagine, Libre3D, NIH 3D Print Exchange, etc.) publishing thousands of designs an exponential growth of open-source designs for 3D printing has been observed and is expected to continue grow [8]. This growth is being fueled at the consumer level because 3D printers have been proven to be an economically beneficial purchase for the developed-world middle-class [8] and those in the maker community [11-13].

In the maker community poly-lactic acid (PLA) is the most popular FFF 3D printing material and is available for the vast majority of 3D printing supplies vendors. PLA has a relatively low melting point (150°-160° C), which requires less energy to print with than other materials and provides a distinct advantage for off-grid applications in the developing world [14-16]. In addition, PLA has been shown to be a safer alternative to ABS, the second most popular 3D printing material as gaged by availability [17,18]. The mechanical properties of 3D printed PLA have been investigated in some detail [19,20]. However, there are many other materials available on the market for prosumer (producing consumer) FFF 3D printing including nylon, polycarbonate (PC), high-density polyethylene (HDPE), high impact polystyrene (HIPS), and others [21]. As novel and affordable 3D printing technologies continue to develop the types of materials that may become common for FFF is expected to grow [22,23] and involve the use of additives [24] (i.e., strengthening agents) to common 3D printable materials [25,26]. Other techniques involve treating 3D printable materials to increase strength [27]. With the introduction of the recyclebot [28], an open-source prosumer plastic filament extruder, and its open source technological cousins (e.g. Lyman Filament Extruder, Plastic Bank Extruder, Filastruder, FilaFab, Noztek, Filabot, EWE, Extrusionbot, Filamaker and the Strooder, Felfil (OS)), these potential strengthening mechanisms can be implemented and tested by the end-user (prosumer) directly.

Unfortunately, there is a severe lack of peer-reviewed data and standards relating to these prosumer FFF 3D printing material properties, which limits the ability of prosumers to develop more sophisticated designs. Recent work with closed-source commercial grade powder printers have described what effect the orientation of layers may have on the properties of a printed part [29] and commercial grade fused deposition modeling (FDM, which is the IP limited subset of FFF) printers have shown a strength dependency on different types of infill patterns and internal structures [30,31] and print orientations [32]. Past results have shown that 3D printed parts perform between 65% and 72% as injection molded parts of the same material [33]. Proprietary printers have been used to show a difference in layer adhesion when parts were printed using various fabrication preferences, including temperature [34].

In order for users to manufacture functional items with open source RepRaps, a recent study investigated mechanical properties of PLA and ABS in realistic environmental conditions, which showed RepRap prints can match and even out perform commercial 3D printers using proprietary FDM in terms of tensile strength with the same polymers [19]. A follow up study [20] found that coloring agents altered the microstructure (percentage of crystallinity) and had an impact on the strength as is well established in the literature [35,36]. As the nature of these studies had different 3D printers running at the users chosen optimal conditions, the processing temperatures varies and this has a major impact on print quality and thus strength. These factors added to the inconsistencies found in a random sampling of RepRap users [19] making the strength of individual prints difficult for prosumers to determine.

To expand on this preliminary knowledge this study investigates the mechanical properties of RepRap 3D printed parts using a commercial open-source RepRap (Lulzbot TAZ) for a wide range of materials including: Ninjaflex (5 colors), SemiFlex (4 colors), HIPS (5 colors), T-Glase (5 colors), polycarbonate (1 color), Nylon (2 Types), and ABS (1 color). The samples are tested for tensile strength following ASTM D638 [37]. The results are presented and conclusions are drawn about the mechanical properties of various FFF printing materials to promote the open-source development of RepRap 3D printing.

2. Methods

Ten specimens of each material were printed considering the ASTM D638 standard [37] using Lulzbot TAZ 3.1 [38] and Lulzbot TAZ 4 [39]. All materials are from the same supplier, Lulzbot [40]. Flexible filaments such as Ninjaflex, SemiFlex and Nylon Bridge were printed on Lulzbot 3.1 as the “flexystruder” tool head [41] was installed on it. All other materials, which were rigid were printed using Lulzbot TAZ 4. Cura 15.04 [42], an open source slicer, was used to generate G-code from the specimen model [43]. All specimens were printed indoors in a temperature controlled environment with 100% infill. Additionally, samples were printed with varying extruder temperatures depending on the material. These temperatures and all the materials tested are summarized in Table 1. Other printing parameters such as layer height, speed and custom controls were fine tuned for each material using the supplier's recommendations as a baseline to produce acceptable print quality and uniformity.

Table 1. 3D printing materials, printing temperature and density of the filament.

Material Type	**Printing Temperature (ºC)**	**Density of filament (g/cm^3)**
ABS	230	1.0311
HIPS	230	1.0280
Polycarbonate	250	1.1950
T-Glase	230	1.2767
Nylon	235	1.1277
SemiFlex	230	1.2216
Ninjaflex	230	1.1869

Only the reduced section of the specimen was considered as the gauge length and the extension of the tapering section was ignored. The geometry of the specimens had a thickness of 3.2 mm, width of 13 mm and a gauge length of 60 mm. The density of the unextruded filament was determined by applying Archimedes principle: a small length (around 2”) of the filament was taken and the mass was measured in air (m_1) and in water (m_2) separately on a electronic balance with least count of 0.0001g. The filament density, d_f, was then calculated using the formula:

$$d_f = d_w \times \left(\frac{m_1}{(m_1 - m_2)} \right) \quad (1)$$

where d_w is the density of water. The different colors of the same material were grouped together and measured as the difference in the density between the colors was below the error (+/- 0.001g) of the apparatus. The sample size was ten for each material group. The density of each material group are also included in Table 1.

The slicer (Cura) has an inbuilt mass estimator, which uses a density of 1.244g/cm^3. The slicer showed a mass of 11.6g for the geometry. This was used to determine the volume to estimate the ideal mass of the specimen for each material type using the measured density.

Ten printed tensile samples for each material/color combination were then subjected to tensile testing consistent with ASTM D638 standards [37]. The rigid specimens were tested for tensile strength on INSTRON 4206 with a 10kN load cell for load measurement and cross head data was used for the extension measurement. Test Works 4 [44] was used to perform the tests. It should be noted, that a 2” extensometer was initially used for measuring the extension of rigid materials. However, most of the samples broke close to the neck, and significant extensions were observed outside the extensometer range. Hence cross head data was used uniformly for all materials. Maximum tensile stress values and corresponding strain values were obtained for rigid materials.

The extension of flexible materials (Ninjaflex, SemiFlex, and Nylon Bridge) was found to be greater than allowed by the INSTRON 4206, hence flexible materials were tested on INSTRON 4210 using the same load cell and Bluehill 2 software [45]. Most of the flexible materials did not break using the INSTRON 4210, and the proportionality limit was found to be very low. Hence, stress-load values at a particular extension value (60mm) were measured for comparison between the different materials and colors.

The orientation of all the rigid materials was diagonal (diagonal to the direction of the pull). The flexible materials were printed in two different orientations to compare the difference in flexibility between the orientations. The orientations printed were vertical (along the direction of the pull) and diagonal.

3. Results and Discussion

The results of the tensile tests for the 3D printed materials are summarized in Table 2 and 3 for rigid and semi-flexible materials, respectively.

Table 2. The average maximum extension (mm), average maximum load (N), average mass (g) and average tensile stress (MPa) for all the 3D printed rigid materials.

Material	**Average maximum extension (mm)**	**Average maximum Load (N)**	**Average Mass (g)**	**Average Maximum Tensile Stress (MPa)**	**Standard deviation of maximum Tensile Stress (MPa)**

ABS	3.70	1196.12	8.70	28.75	3.15
HIPS (black)	4.52	813.09	8.83	19.55	2.15
HIPS (Blue)	3.20	832.67	9.58	20.02	1.61
HIPS (White)	3.04	882.51	9.00	21.21	0.88
HIPS (Clear)	4.91	890.48	9.00	21.41	0.55
HIPS (Gray)	3.48	888.05	9.21	21.35	1.14
Nylon 618	41.71	1314.42	11.79	31.60	3.20
Polycarbonate	8.57	2041.64	9.89	49.08	3.03
T-Glase (Gray)	5.77	1241.89	10.44	28.79	3.26
T-Glase (Clear)	6.22	1312.85	10.34	31.56	2.81
T-Glase (Blue)	6.31	1360.52	10.73	32.70	3.98
T-Glase (Green)	5.65	1470.97	11.17	35.36	5.47
T-Glase (Red)	5.50	1428.28	10.39	34.33	5.51

Table 3. The orientation of the print, average mass (g), average load at 60mm extension (N) and average stress at 60mm extension (MPa) for the semi-flexible materials.

Material	**Orientation of print**	**Average Mass(g)**	**Average Load at 60mm extension (N)**	**Average Stress at 60mm extension (MPa)**	**Standard deviation of Stress at 60mm extension (MPa)**
Ninjaflex (Black)	Diagonal	11.27	202.79	4.87	0.25
Ninjaflex (Blue)	Diagonal	8.86	147.62	3.55	0.64
Ninjaflex (Green)	Vertical	10.92	211.75	5.09	0.15
Ninjaflex (Red)	Diagonal	11.355	199.64	4.8	0.28
Ninjaflex (White)	Vertical	9.192	161.88	3.89	0.1
Nylon Bridge	Diagonal	10.666	1102.87	26.51	3.65
SemiFlex (Black)	Diagonal	12.14	422.04	10.15	1.02
SemiFlex (Blue)	Diagonal	12.08	416.88	10.02	0.58
SemiFlex (Red)	Vertical	10.65	382.37	9.2	0.89
SemiFlex (Red)	Diagonal	11.41	406.89	9.78	1.18
SemiFlex (White)	Vertical	9.94	348.72	8.38	0.65

Analysis of load and mass for all the materials shows a significant co-relation between mass of the specimen and the load. This is apparent in Figures 1-8, which show the load as a function of mass for ABS, HIPS, nylon 618, polycarbonate, T-Glase, NinjaFlex, Nylon Bridge, and SemiFlex, respectively.

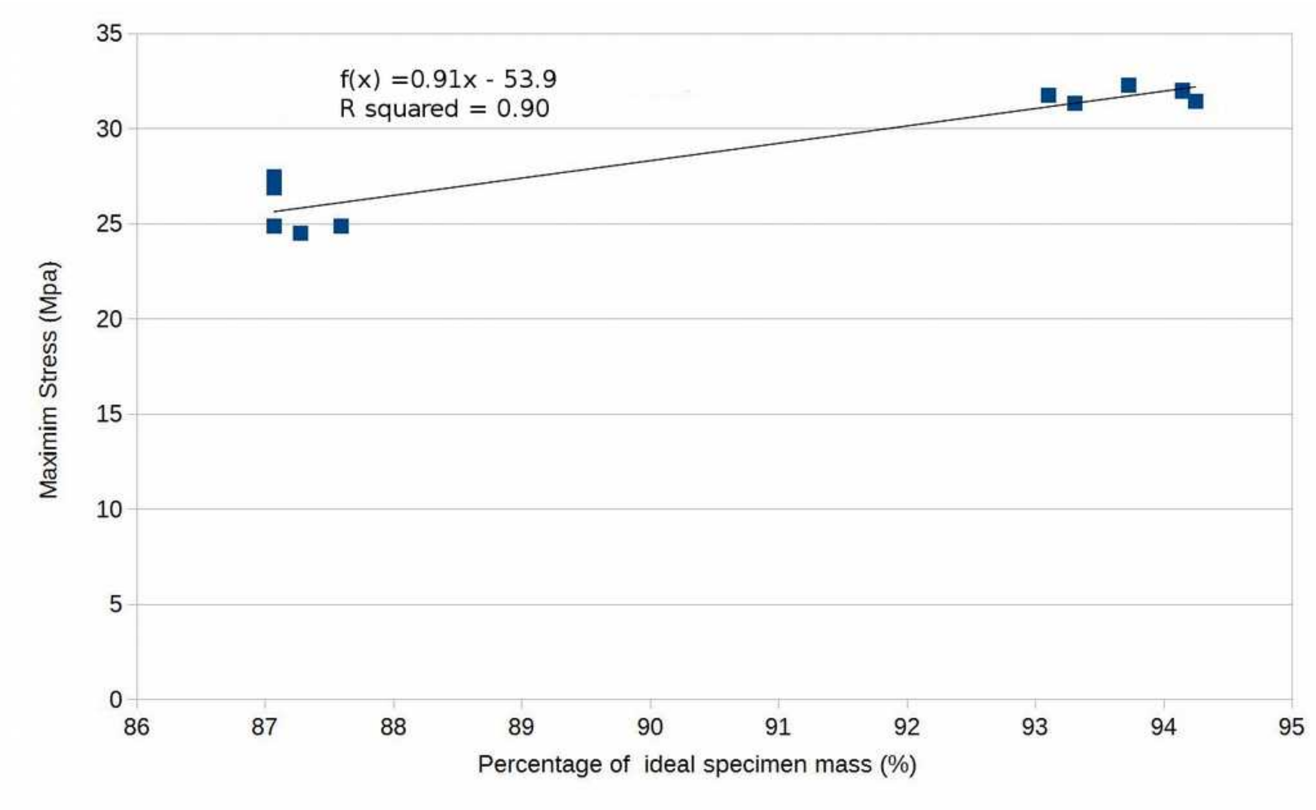

Figure 1. The maximum stress (MPa) of ABS as a function of sample mass to filament mass percentage.

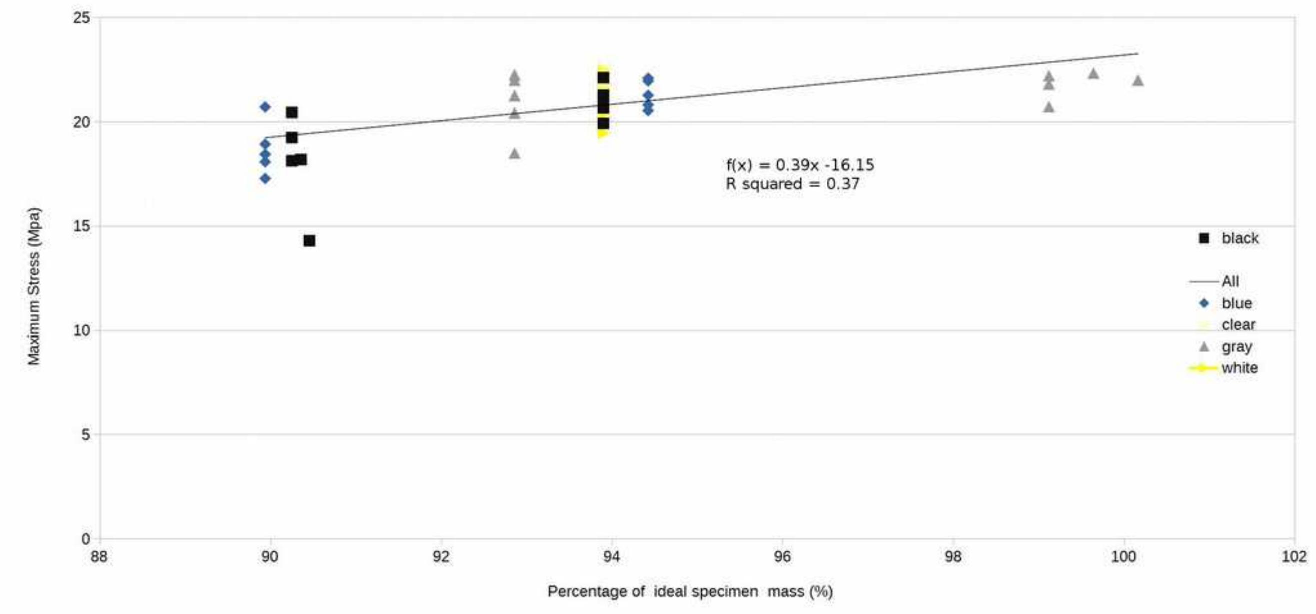

Figure 2. The maximum stress (MPa) of HIPS as a function of sample mass to filament mass percentage.

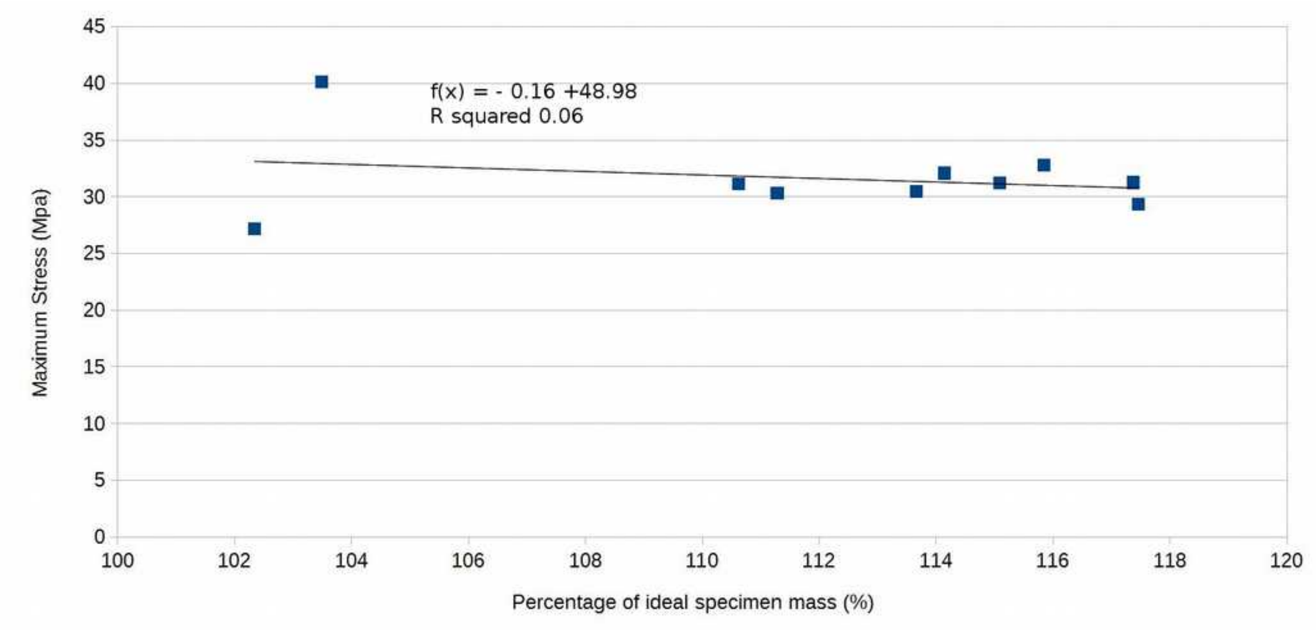

Figure 3. The maximum stress (MPa) of Nylon 618 as a function of sample mass to filament mass percentage.

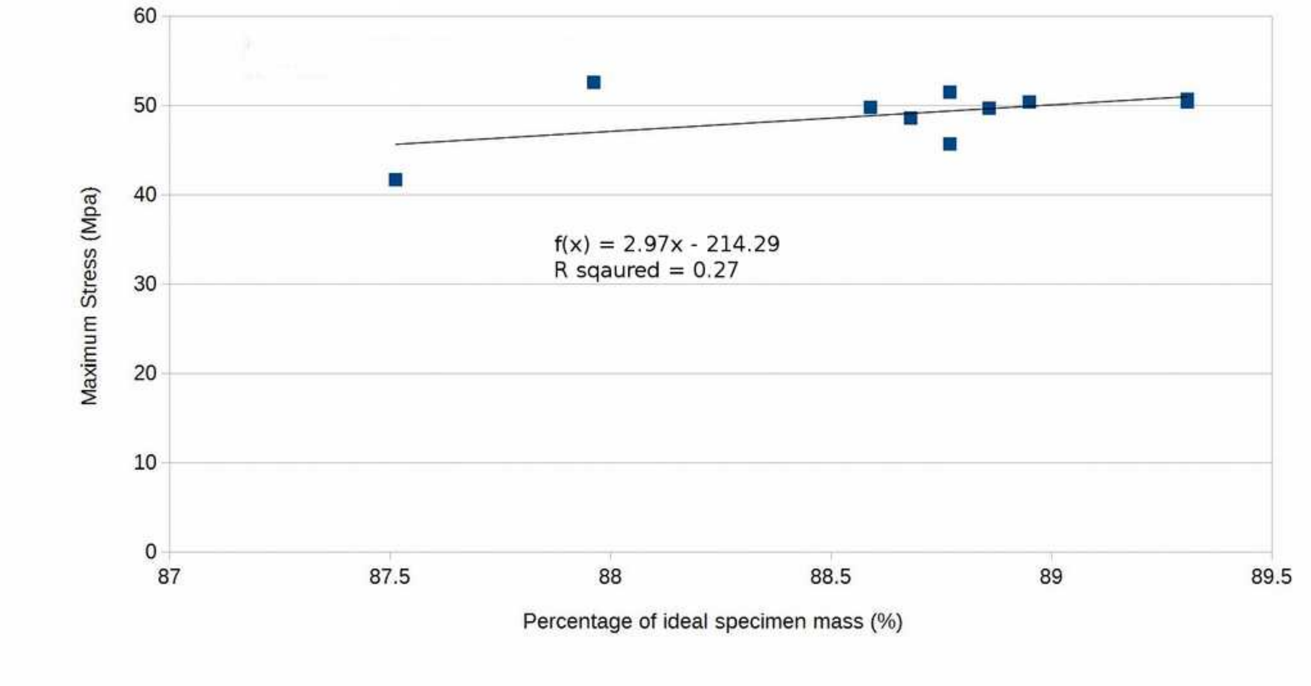

Figure 4. The maximum stress (MPa) of polycarbonate as a function of sample mass to filament mass percentage.

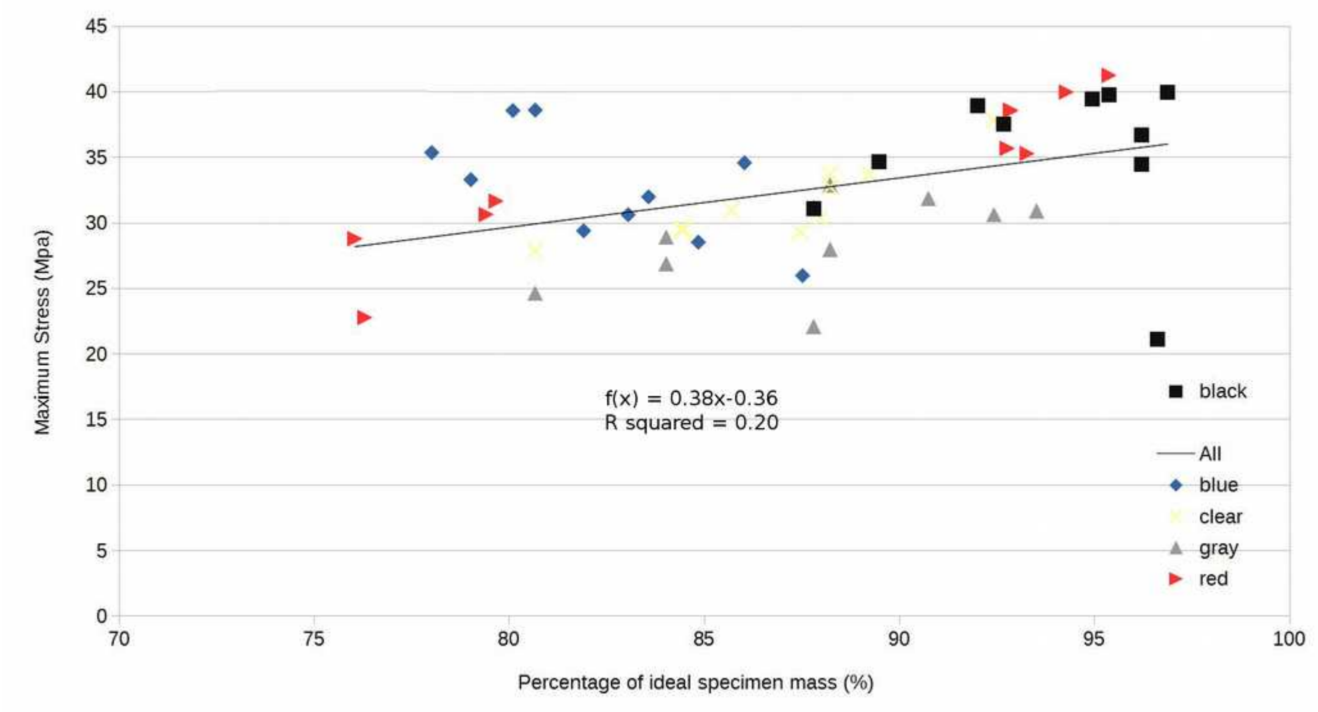

Figure 5. The maximum stress (MPa) of T-Glase as a function of sample mass to filament mass percentage.

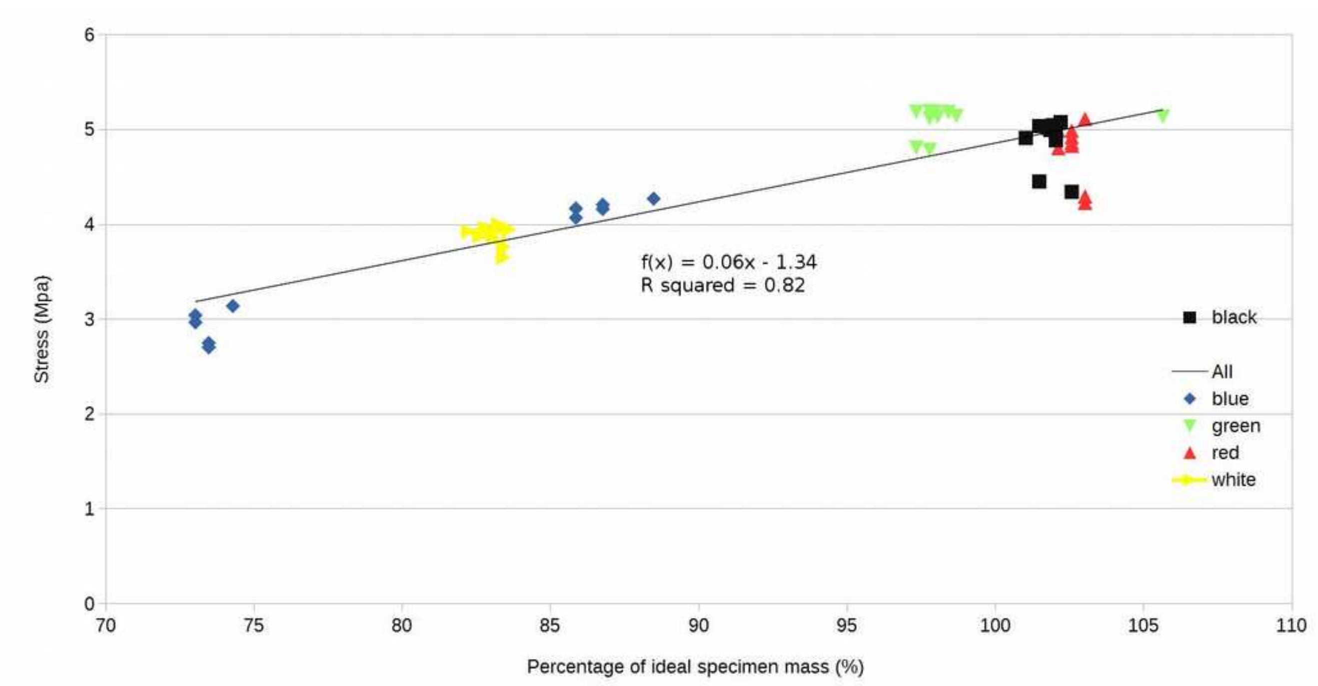

Figure 6. Stress at 60mm extension (MPa) of Ninjaflex as a function of sample mass to filament mass percentage.

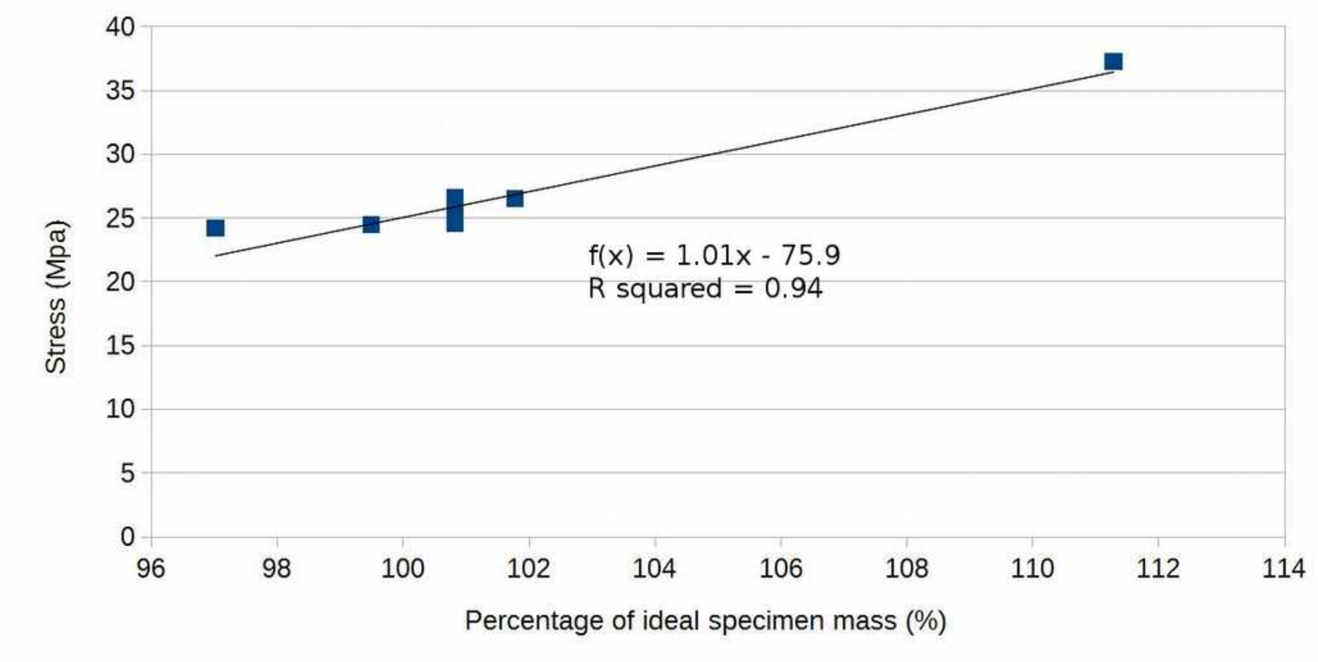

Figure 7. Stress at 60mm extension (MPa) of Nylon Bridge as a function of sample mass to filament mass percentage.

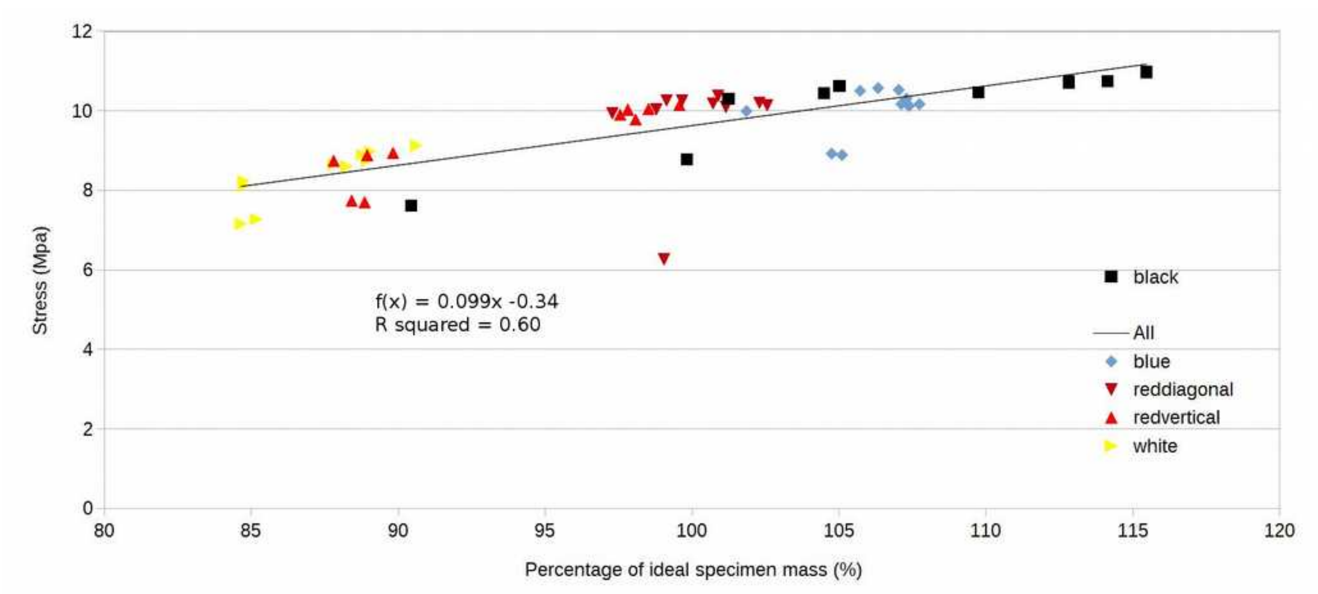

Figure 8. Stress at 60mm extension (MPa) of SemiFlex as a function of sample mass to filament mass percentage.

As can be seen in the results of Figures 1-8, the strongest material among those tested was polycarbonate with a maximum tensile strength of 49.08 MPa. The most flexible material was Ninjaflex, which did not break after an extension of about 800%. The tensile stress for Ninjaflex at 800% extension was 12.69 MPa (average of all colors). Nylon materials were stronger than Ninjaflex and SemiFlex, and much more flexible than ABS, HIPS, T-Glase, and polycarbonate, providing a good balance between strength and flexibility. It is also clear from the materials where multiple colors were tested (HIPS in Figure 2, T-Glase in Figure 5, Ninjaflex in Figure 6 and SemiFlex in Figure 8) that color of the material can have a significant impact on the maximum stress a 3D printed material can withstand. It should also be pointed out, that although the variance within a single material and color is small for most tests, some significant variance was still observed indicating the need for conservative safety factors for mechanically important components.

It can be seen in the trend lines that for the majority of the samples the strength is proportional to the mass of the specimen. This is quantified in Table 4, where the correlation coefficients are shown for each material family. Nylon 618 is the only material that shows a negative correlation and careful inspection of the data indicates that there is not a correlation as the error in the fit is by far the worst in all the materials tested.

Table 4. Correlation coefficients as a function of 3D printed material.

Material	Correlation Coefficient
ABS	0.91
HIPS	0.39
Nylon 618	-0.15
PC	2.97
T-Glase	0.38
NinjaFlex	0.06
Nylon Bridge	1.00
SemiFlex	0.10

It has been shown that crystallinity of the printed material has effects on the tensile strength of a color [20]. The crystallinity difference between various colors may be due to addition of coloring agents. In general for all of the materials the color has an effect on the percentage of an ideal specimen, which in turn effects the mechanical properties. Each color has a slightly different optimum temperature for printing. The mass of different colors may be different due to various other factors such as: slight difference in density, moisture, and weaker chemical bonds due to addition of coloring agent. Currently, the coloring agents and other additives to the commercial filament suppliers is not known. This points to the necessity of the open source developmental model, which has been so successful in 3D printing itself to be expanded beyond materials science software [46-51] to open source materials development [24,52,53]. This can occur within the maker community itself (e.g. openmaterials.org) or as recyclebot technology is investigated [54-56] and deployed throughout the developing world to produce ethical filament or fair trade filament [57-59].

Despite these limitations it is possible to reliably estimate the strength of a 3D printed with a known plastic. Based on the results of this study a two part process can be followed to have a reasonably high expectation that a part will have tensile strengths described here for a given material. The two-step process is illustrated in Figure 9.

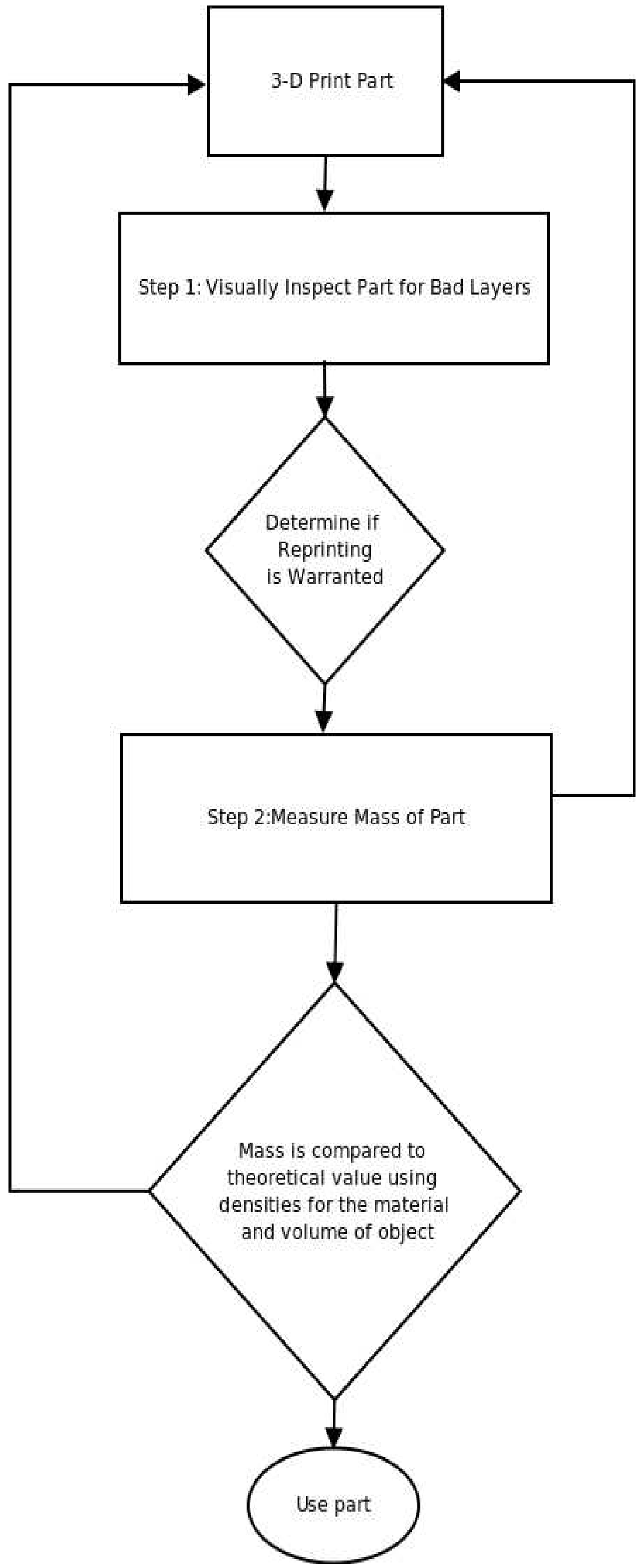
3-D Print Part
Step 1: Visually Inspect Part for Bad Layers
Determine if Reprinting is Warranted
Step 2:Measure Mass of Part
Mass is compared to theoretical value using densities for the material and volume of object
Use part

Figure 9. Illustration of low-cost two step process to determine under extrusion in 3D printed part.

First, the exterior of the print should be inspected for sub-optimal layers from under extrusion. If for example, under extrusions are detected on the outer surface as shown in Figure 10, then the part should be reprinted if mechanical stability is important for the specific application. Second, in order to determine if there has been any under-extrusion in the interior, the mass of the samples is measured. Prosumers without access to lab grade scales can use a digital food balance to get acceptable precision and accuracy. This mass is compared to the theoretical value using the densities from Table 1 for the material and the volume of the object.

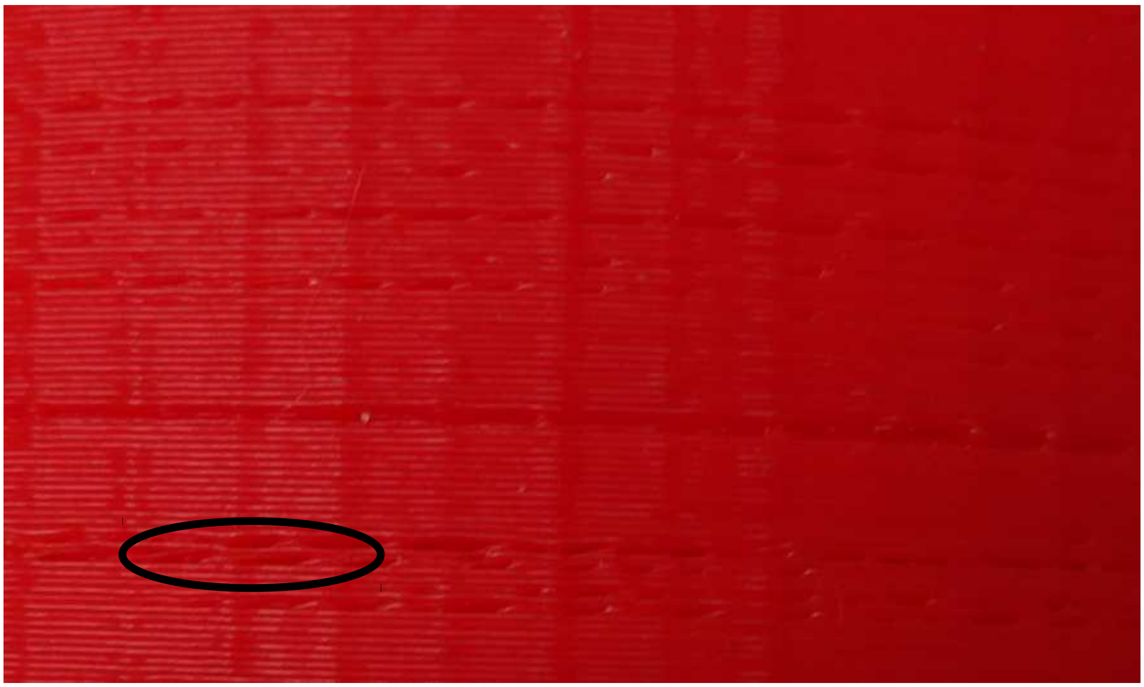

Figure 10. Under extrusion on exterior surface of 3D printed object (observable as dark lines).

There are many applications of materials with high tensile strength and flexibility in prosumer FFF distributed manufacturing. First, many practical applications of open source appropriate technologies (OSAT) for the developing world demand high strength materials [6,61-63]. For example, hand tools used by organic farmers on small farms need to the strength available from higher performance materials to be practical [64]. These same tools could be used in gardens in the developed world. The use of flexible materials, such as SemiFlex, Nylon Bridge and NinjaFlex tested here, similarly open up other applications such as components that come directly in contact with humans such as hand grips, watch bands, shoes [65], belts and face mask rings. Flexible materials are also good for shock absorbing outer coverings on sensitive equipment and providing a better grip for users [66]. Flexible materials can also be used to make custom insoles and orthotics [67]. Technical applications of such flexible materials would include timing belts, gaskets, air bladders, o-rings, shock absorbtion and vibration dampening.

This study has some limitations. The density of the samples is measured for a material group and not for individual colors of the same material. There may be a small difference in density among the various colors, which may explain the mass difference between the colors of a material. The density measured depends on the density of the water, and various environmental factors that can produce slight errors. Although such errors would be insignificant in most other cases, the filaments in this study have densities close to the density of water, which can create significance. It should also be pointed out that the cross head extension is applied only to the reduced section of the specimen. The tapering section will have some extension, but it would effect the strain values only, not the maximum stress value, which is the focus of this study. Load differences due to orientations was limited only for two materials in this study, but has been observed previously [30-32].

These limitations lead to several potential sources of future work. The reasons behind the difference in mass for various specimens can be studied in a fully controlled and measurable environment. The material can also be printed with the length of the specimen being vertical on the printer and tensile strength can be tested. This direction is the weakest of the axes as there are gaps between the layers of seemingly solid infill in FFF [20]. In addition, the impact of the geometry of the part need further study to determine the limitations of FFF for manufacturing [60]. Materials can undergo significant property changes during storage. To account for this an identical material subjected to different storage conditions both pre and post printing and subsequently tested can help determine the environmental sensitivity of 3D printing materials. Finally, as the prosumer 3D printer material market continues to expand there will be other materials (e.g. polymaker PC-plus) and composites that could be useful for mechanically loaded parts, which will need to be tested.

Conclusions

The study clearly demonstrates that the tensile strength of a 3D printed specimen depends largely on the mass of the specimen, for all materials. This dependence enables prosumers to solve the challenge of unknown print quality effects on the mechanical properties of a 3D printed part using a two step process to estimate the tensile strengths for a given material. First, the exterior of the print is inspected visually for sub-optimal layers from under or over extrusion. Then, to determine if there has been under-extrusion in the interior, the mass of samples is measured. This mass is compared to what the theoretical value is using the densities provided in this study for the material and the volume of the object. This two step process provides a means to assist low-cost open-source 3D printers expand their range of object production to functional parts. The strongest material among those tested was polycarbonate with a maximum tensile strength of 49 MPa. The most flexible material was Ninjaflex, which did not break after an extension of about 800%. The tensile stress for Ninjaflex at 800% extension was over 12 MPa (average of all colors). Nylon materials were stronger than Ninjaflex and SemiFlex, and much more flexible than ABS, HIPS, T-Glase, and polycarbonate, which provides a good balance between strength and flexibility.

Acknowledgements

The authors would like to thank Aleph Objects, Inc for support and technical assistance.

References

1. E. Sells, Z. Smith, S. Bailard, A. Bowyer, and V. Olliver, RepRap: The Replicating Rapid Prototyper: Maximizing Customizability by Breeding the Means of Production, In Piller, F. T., and Tseng, M. M., Handbook of Research in Mass Customization and Personalization: Strategies and concepts (Vol. 1), World Scientific. (2010)
2. R. Jones, P. Haufe, E. Sells, P. Iravani, V. Olliver, C. Palmer, and A. Bowyer, RepRap – the replicating rapid prototyper, Robotica. 29(01) (2011) 177–191.
3. A. Bowyer, 2014. 3D printing and humanity's first imperfect replicator. 3D printing and additive manufacturing, 1(1), 4-5.
4. G. Rundle, 2014. A Revolution in the Making. Affirm Press; South Melbourne.
5. J. Moilanen, V. Tere, Manufacturing in motion: first survey on 3D printing community. [Online] Available: http://surveys.peerproduction.net/2012/05/manufacturing-in-motion/. [Accessed: 22-Nov-2014].
6. J. M. Pearce, C. M. Blair, K. J. Laciak, R. Andrews, A. Nosrat, and I. Zelenika-Zovko, 3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development, J. Sustain. Dev. 3(4) (2010) 17.
7. C. Mota, The Rise of Personal Fabrication, in Proceedings of the 8th ACM Conference on Creativity and Cognition, New York, NY, USA, (2011) 279–288.
8. B. T. Wittbrodt, A. G. Glover, J. Laureto, G. C. Anzalone, D. Oppliger, J. L. Irwin, and J. M. Pearce, Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers, Mechatronics, 23(6) (2013) 713–726.
9. M. Kreiger and J. M. Pearce, Environmental Impacts of Distributed Manufacturing from 3-D Printing of Polymer Components and Products, in Symposium D/G – Materials for Sustainable Development—Challenges and Opportunities. 1492 (2013) 85–90.
10. M. Kreiger and J. M. Pearce, Environmental Impacts of Distributed Manufacturing from 3-D Printing of Polymer Components and Products. MRS Online Proceedings Library, 1492, mrsf12-1492-g01-02 (2013).
11. J. G. Tanenbaum, A. M. Williams, A. Desjardins, and K. Tanenbaum, Democratizing Technology: Pleasure, Utility and Expressiveness in DIY and Maker Practice, in Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, New York, NY, USA, (2013) 2603–2612.
12. I. Mohomed & P. Dutta, (2015). The Age of DIY and Dawn of the Maker Movement. ACM SIGMOBILE Mobile Computing and Communications Review, 18(4), 41-43.
13. J. L. Irwin, Pearce, J. M., Anzolone, G., & Oppliger, D. E. 2014. The RepRap 3-D Printer Revolution in STEM Education. – In: 121st ASEE Annual Conference & Exposition. Available at http://www.asee.org/file_server/papers/attachment/file/0004/4989/asee_reprap_paper_final1.pdf
14. D. L. King, A. Babasola, J. Rozario, and J. M. Pearce, Mobile Open-Source Solar-Powered 3-D Printers for Distributed Manufacturing in Off-Grid Communities, Challenges in Sustainability 2(1) (2014) 18-27.
15. K.Y. Khan, Gauchia, L., & & Pearce, J.M. 2015. Self-Sufficiency of 3-D Printers: Utilizing Stand-alone Solar Photovoltaic Power Systems. - 3-D Printed Materials and Systems (in press).
16. J. Gwamuri, D. Franco, K. Y. Khan, L. Gauchia and J. M. Pearce. High-Efficiency Solar-Powered 3-D Printers for Sustainable Development. *Machines* 2016, **4**(1), 3; doi: 10.3390/machines4010003

17. M. Groenendyk and R. Gallant, 3D printing and scanning at the Dalhousie University Libraries: a pilot project, Libr. Hi Tech. 31(1) (2013) 34–41.
18. D.F. Merlo, Ing, D. and Mazzoni, S., Gas evolution during FDM 3D printing and health impact. 3D Safety.org http://www.3dsafety.org/3dsafety/download/mf2015_eng.pdf
19. B. M. Tymrak, M. Kreiger, and J. M. Pearce, Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions, Mater. Des. 58 (2014) 242–246.
20. B. Wittbrodt & Pearce, J. M. (2015). The effects of PLA color on material properties of 3-D printed components. *Additive Manufacturing*, *8*, pp.110-116.
21. E. J. Hunt, C. Zhang, N. Anzalone, and J. M. Pearce, Polymer Recycling Codes for Distributed Manufacturing with 3-D printers, Resources, Conservation and Recycling 97 (2015) 24-30.
22. D. T. Pham and R. S. Gault, A comparison of rapid prototyping technologies, Int. J. Mach. Tools Manuf. 38(10–11) (1998) 1257–1287.
23. X. Yan and P. Gu, A review of rapid prototyping technologies and systems, Comput.-Aided Des. 28(4) (1996) 307–318.
24. J. M. Pearce. A novel approach to obviousness: An algorithm for identifying prior art concerning 3-D printing material. World Patent Information **42**, 13–18 (2015). doi:10.1016/j.wpi.2015.07.003
25. A. R. T. Perez, D. A. Roberson, and R. B. Wicker, Fracture Surface Analysis of 3D-Printed Tensile Specimens of Novel ABS-Based Materials, J. Fail. Anal. Prev. 14(3) (2014) 343–353.
26. B. G. Compton and J. A. Lewis, 3D-Printing of Lightweight Cellular Composites, Adv. Mater. 26(34) (2014) 5930–5935.
27. S. Shaffer, K. Yang, J. Vargas, M. A. Di Prima, and W. Voit, On reducing anisotropy in 3D printed polymers via ionizing radiation, Polymer. 55(23) (2014) 5969–5979.
28. C. Baechler, M. DeVuono, and J. M. Pearce, Distributed recycling of waste polymer into RepRap feedstock, Rapid Prototyp. J. 19(2) (2013) 118–125.
29. V. Vega, J. Clements, T. Lam, A. Abad, B. Fritz, N. Ula, and O. S. Es-Said, The Effect of Layer Orientation on the Mechanical Properties and Microstructure of a Polymer, J. Mater. Eng. Perform. 20(6) (2011) 978–988.
30. L. Rosas, Characterization of Parametric Internal Structures for Components Built by Fused Deposition Modeling, University of Windsor. (2013).
31. T. Letcher, Rankouhi, B. and Javadpour, S., 2015, November. Experimental Study of Mechanical Properties of Additively Manufactured ABS Plastic as a Function of Layer Parameters. In *ASME 2015 International Mechanical Engineering Congress and Exposition* (pp. V02AT02A018-V02AT02A018). American Society of Mechanical Engineers.
32. J. Cantrell, Rohde, S., Damiani, D., Gurnani, R., DiSandro, L., Anton, J., Young, A., Jerez, A., Steinbach, D., Kroese, C. and Ifju, P., Experimental Characterization of the Mechanical Properties of 3D-Printed ABS and Polycarbonate Parts. Available: http://cimar.mae.ufl.edu/rapid_proto/pages/3D%20Printing%20Paper%20Final%20Manuscript.pdf
33. S. Ahn, M. Montero, D. Odell, S. Roundy, and P. K. Wright, Anisotropic material properties of fused deposition modeling ABS, Rapid Prototyp. J. 8(4) (2002) 248–257.
34. Q. Sun, G.M. Rizvi, C.T. Bellehumeur, and P. Gu, Effect of processing conditions on the bonding quality of FDM polymer filaments, Rapid Prototyp. J. 14(2) (2008) 72–80.

35. D. G. Brady, The crystallinity of poly(phenylene sulfide) and its effect on polymer properties, J. Appl. Polym. Sci. 20(9) (1976) 2541–2551.
36. D. M. Lincoln, R. A. Vaia, Z.-G. Wang, B. S. Hsiao, and R. Krishnamoorti, Temperature dependence of polymer crystalline morphology in nylon 6/montmorillonite nanocomposites, Polymer. 42(25) (2001) 09975–09985.
37. ASTM. Standard Test Method for Tensile Properties of Plastics. ASTM D638. ASTM International. 2010.
38. Lulzbot TAZ 3.1 https://download.lulzbot.com/TAZ/3.1/
39. Lulzbot TAZ 4 https://download.lulzbot.com/TAZ/4.0/
40. Lulzbot. Filament. https://www.lulzbot.com/store/filament
41. Lulzbot Flexystruder_v2 http://download.lulzbot.com/Mini/accessories/Flexystruder_v2/
42. Cura 15.04. https://ultimaker.com/en/products/cura-software
43. B. M. Tymrak, ASTM Tensile Test Specimen, Thingiverse. [Online]. Available: http://www.thingiverse.com/thing:13694. [Accessed: 22-Nov-2014].
44. Test works 4 https://www.mts.com/ucm/groups/public/documents/library/mts_005085.pdf
45. Bluehill 2 http://www.msm.cam.ac.uk/mechtest/docs/WB1193B~Bluehill2 Brochure.pdf
46. IV Powell A.C. and Arroyave, R., 2008. Open source software for materials and process modeling. *JOM*, *60*(5), pp.32-39.
47. P. Giannozzi, , Baroni, S., Bonini, N., Calandra, M., Car, R., Cavazzoni, C., Ceresoli, D., Chiarotti, G.L., Cococcioni, M., Dabo, I. and Dal Corso, A., 2009. QUANTUM ESPRESSO: a modular and open-source software project for quantum simulations of materials. *Journal of Physics: Condensed Matter*, *21*(39), p.395502.
48. S.P. Ong, Richards, W.D., Jain, A., Hautier, G., Kocher, M., Cholia, S., Gunter, D., Chevrier, V.L., Persson, K.A. and Ceder, G., 2013. Python Materials Genomics (pymatgen): A robust, open-source python library for materials analysis. *Computational Materials Science*, *68*, pp.314-319.
49. X.Gonze, Beuken, J.M., Caracas, R., Detraux, F., Fuchs, M., Rignanese, G.M., Sindic, L., Verstraete, M., Zerah, G., Jollet, F. and Torrent, M., 2002. First-principles computation of material properties: the ABINIT software project. *Computational Materials Science*, *25*(3), pp.478-492.
50. B.H. Toby, and Von Dreele, R.B., 2013. GSAS-II: the genesis of a modern open-source all purpose crystallography software package. *Journal of Applied Crystallography*, *46*(2), pp.544-549.
51. N.M. OLBoyle, Banck, M., James, C.A., Morley, C., Vandermeersch, T. and Hutchison, G.R., 2011. Open Babel: An open chemical toolbox. *J Cheminf*, *3*, p.33.
52. J.M. Pearce, 2012. Physics: Make nanotechnology research open-source. *Nature*, *491*(7425), pp.519-521.
53. A. Jain, Ong, S.P., Hautier, G., Chen, W., Richards, W.D., Dacek, S., Cholia, S., Gunter, D., Skinner, D., Ceder, G. and Persson, K.A., 2013. Commentary: The Materials Project: A materials genome approach to accelerating materials innovation. *Apl Materials*, *1*(1), p.011002.
54. F. Cruz, Lanza, S., Boudaoud, H., Hoppe, S. and Camargo, M., Polymer Recycling and Additive Manufacturing in an Open Source context: Optimization of processes and methods. Available: http://sffsymposium.engr.utexas.edu/sites/default/files/2015/2015-127-Cruz.pdf

55. M.A Kreiger, Mulder, M.L., Glover, A.G. and Pearce, J.M., 2014. Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. *Journal of Cleaner Production*, *70*, pp.90-96.
56. S. Chonga, Chiub, H.L., Liaob, Y.C., Hungc, S.T. and Pand, G.T., 2015. Cradle to Cradle® Design for 3D Printing. *CHEMICAL ENGINEERING*, *45*.
57. S.R. Feeley, Wijnen, B. and Pearce, J.M., 2014. Evaluation of potential fair trade standards for an ethical 3-D printing filament. *Journal of Sustainable Development*, 7(5), 1-12. DOI: 10.5539/jsd.v7n5p1
58. P. Marks, , 2014. Plastic fantastic. *New Scientist*, *223*(2978), p.24.
59. T. Birtchnell, and Hoyle, W., 2014. 3D4D Indicators and Forerunners. In *3D Printing for Development in the Global South: The 3D4D Challenge* (pp. 96-112). Palgrave Macmillan UK.
60. M.Fernandez-Vicente, Canyada, M. and Conejero, A., 2015. Identifying limitations for design for manufacturing with desktop FFF 3D printers. *International Journal of Rapid Manufacturing*, *5*(1), pp.116-128.
61. M. Gebler, A.J.S. Uiterkamp, and C. Visser, 2014. A global sustainability perspective on 3D printing technologies. *Energy Policy*, *74*, pp.158-167.
62. J.M. Pearce, 2012. The case for open source appropriate technology. *Environment, Development and Sustainability*, *14*(3), pp.425-431.
63. S. Mayson, 2013. People-Centred Desktop Design and Manufacture: A review of web enabled open source tools for localised community focused inclusive design. *Include Asia 2013: Global Challenges and Local Solutions in Inclusive Design*, pp.1-10.
64. J.M. Pearce, 2015. Applications of open source 3-D printing on small farms. *Organic Farming*, *1*(1), pp.19-35.
65. J. Micallef, 2015. What’s Possible with 3D Printing?. In *Beginning Design for 3D Printing* (pp. 1-30). Apress.
66. B.T. Wittbrodt, D.A. Squires, J. Walbeck, E. Campbell, W.H. Campbell. J.M. Pearce, 2015. Open-Source Photometric System for Enzymatic Nitrate Quantification. *PloS one*, *10*(8), p.e0134989.
67. M. Yarwindran, N.A. Sa’aban, M. Ibrahim, and R. Periyasamy, 2006. Thermoplastic Elastomre Infill Pattern Impact on Mechanical Properties of 3D Printed Customized Orthotic Insole. ARPN Journal of Engineering and Applied Sciences 11, 10, 6519-6524.