Mechanical Properties and Microstructures of Thermoplastic Materials Printed by 3-Dimensional (3D) Printers

RAYMOND K.F. LAM, Queensborough Community College, New York, U.S.A.
MERGON PIERRE, Queensborough Community College, New York, U.S.A.
BERNARD HUNTER, Queensborough Community College, New York, U.S.A.
JOSEPH SEITER, Queensborough Community College, New York, U.S.A.
MICHAEL LAWRENCE, Queensborough Community College, New York, U.S.A.

This study investigated mechanical properties and microstructures of 3D printable thermoplastics including acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate (ASA), PolyJet VeroCyan RGD843, and Nylon12CF material printed by uPrint SE Plus, Stratasys Fortus 450mc, and Stratasys J750 3-dimensional printers. 3D deposition processes of fused deposition modeling (FDM) process and PolyJet process were employed to manufacture test specimens. The specimens were printed at raster orientation angles of 0 degree, 45 degrees, and 90 degrees; and at build orientations of flat and up-right to determine the directional properties of the materials. Specimens were subjected to tensile test using a tensile testing machine to measure stress and strain. Scanning electron microscopy was utilized to examine specimen microstructures after the tensile test for correlating effects of microstructure to stress and strain data. Failure mode was discussed. Yield strength, tensile strength, rupture strength, Poisson's ratio, modulus of elasticity, elongation at break, and microstructure effects on the mechanical properties for each combination of raster orientation angle and build orientation were determined. Mechanical properties and microstructures of 3D printed materials were compared.

1. INTRODUCTION

Experts predict that the impact and adoption rate of 3-dimensional (3D) printing in manufacturing will increase dramatically over the next 5 years. The market for 3D printing technology itself is expected to grow to $5.2 billion by 2020 [1]. One example is General Electric (GE)'s decision to deploy 3D printers to manufacture nozzles for its LEAP engines. GE Aviation projects will have printed more than 100,000 additive parts by 2020 [2]. Engineering components printed by 3-dimensional (3D) printers are employed as mechanical structures in an assembly. In order for the printed components to be useful for engineering applications, mechanical properties of printed parts must be known for structural design. The properties provide answers to the strength of the material, the kinds of stresses a component can endure before failure, and the size of a component based on the loads it experiences. 3D printed materials had recently been studied for their mechanical properties [3, 4, 5]. Relationships between mechanical strength and microstructure were generally not examined. This study was undertaken to further understand the mechanical properties and microstructures of thermoplastic materials printed by 3D printers.

2. EXPERIMENT

Thermoplastic materials of acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate (ASA), PolyJet VeroCyan RGD843, and Nylon12CF were printed by uPrint SE Plus, Stratasys Fortus 450mc, and Stratasys J750 3-dimensional printers. The ASA materials included white and green color materials. The PolyJet VeroCyan RGD843 and Nylon12CF were materials provided by Stratasys. The Nylon12CF is a composite material with a matrix of nylon imbedded with carbon fibers. 3D deposition processes of fused deposition modeling (FDM) process and PolyJet process were utilized to print specimens. The ABS specimens were printed using FDM by the uPrint SE Plus printer, the ASA material using FDM by the Stratasys Fortus 450mc printer, the PolyJet VeroCyan RGD843 materials using PolyJet process by the Stratasys J750 printer, and the Nylon12CF using FDM by the Stratasys Fortus 450mc printer. Specimens took the dog-bone shape of a standard tensile sample (Figure 1). Each specimen measured 4.75 inches in length. Diameter and length of the two ends of specimen were 1 inch and 0.75 inch, respectively. Diameter of the specimen middle section was 0.5 inch.

The specimens were printed at a combination of raster orientations of 0 degree, 45 degrees, and 90 degrees and build orientations of flat and upright. Figure 2 shows the orientations of each set of specimens printed by a printer. Three specimens were printed flat at 0 degree, 45 degrees, and 90 degrees, respectively, and one specimen was printed at upright orientation. All four specimens were printed at the same time in a run.

Mechanical properties of printed specimens were measured by Tinius Olsen Universal Testing Machine Model 300SL with 60,000 lb_f capacity. A specimen was mounted on the machine and subject to a tensile test (Figure 3). The specimen was pulled by a tensile force until fracture (Figure 4). Applied force and specimen length were continuously measured during the test. Experimental data were captured on a graph. A typical tensile test graph is showed in Figure 5. Specimens were identified as “0”, “45”, “90”, and “up” to represent printing orientation of 0 degree, 45 degrees, 90 degrees, and upright, respectively. Scanning electron microscopy (SEM) of fractured specimen (Figure 6) was carried out in a Hitachi TM-3030 tabletop microscope at an accelerating voltage of 15 kV (Figure 7).

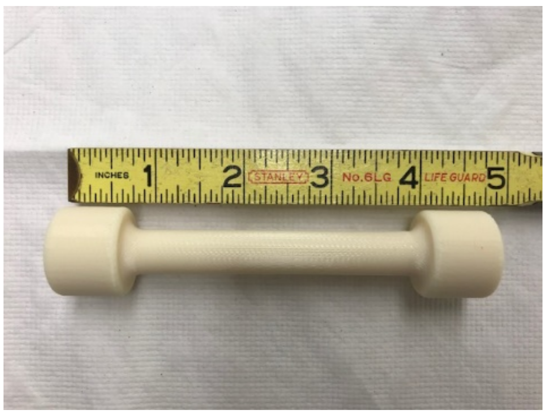

Figure 1. 3D Printed Specimen Before Tensile Test

Figure 2. Orientation of Printed Specimens

Figure 3. Tinius Olsen Universal Testing Machine for Tensile Testing

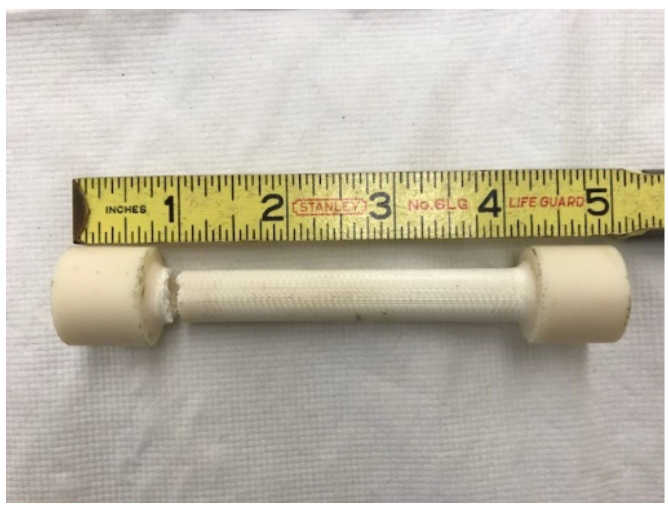

Figure 4. 3D Printer Specimen after Tensile Test

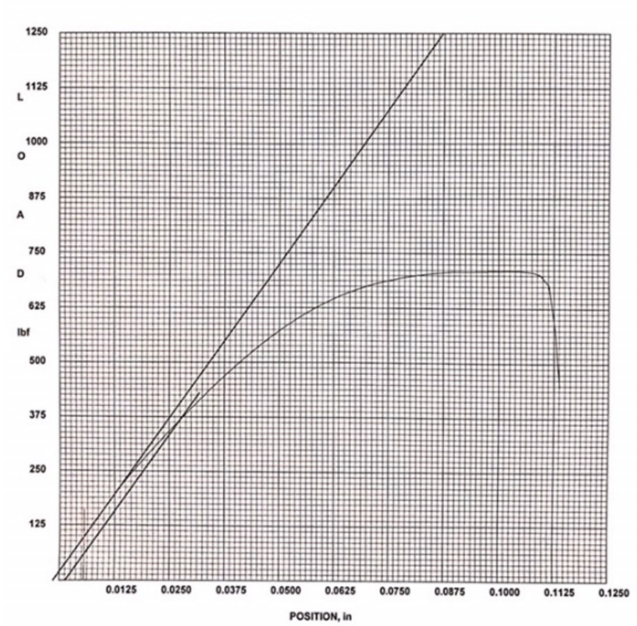

Figure 5. Load versus Position Data Graph from Tensile Tester

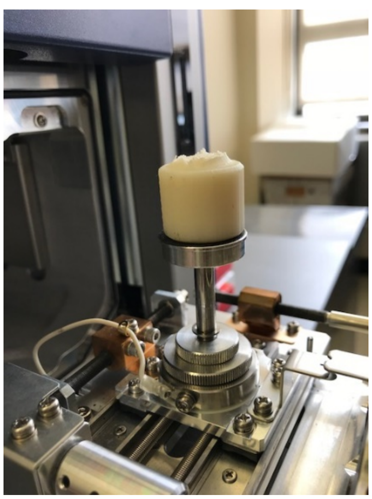
Figure 6. Specimen for Scanning Electronic Microscopy

Figure 7. Hitachi TM-3030 Scanning Electronic Microscope

3. RESULTS AND DISCUSSION

Figure 8 depicts yield strength at 0.2% offset of the thermoplastics. Distinctive patterns in yield strength among printing orientations of flat 0°, flat 45°, and flat 90° of the entire group of thermoplastics were not observed. Yield strengths of those three orientations varied within a range of values, ABS from 637 to 1,402 psi, ASA White from 1,783 to 1,846 psi, ASA Green from 2,101 to 3,565 psi, PolyJet VeroCyan RGD843 from 2,674 to 3,056 psi, and Nylon12CF from 5,730 to 6,366 psi. It was not conclusive if any of the three orientations was more superior or stronger than the others. The upright orientation demonstrated the lowest yield strength among the four orientations. Yield strengths are generally increasing from ABS, ASA white, ASA green, PolyJet VeroCyan RGD843, to Nylon12CF materials.

Figure 9 shows tensile strength of the thermoplastics. The tensile strength behaved similarly as the yield strength. The tensile strengths of orientations of flat 0°, flat 45°, and flat 90° were generally similar and their values of ABS ranged from 895 to 1,660 psi, ASA White from 3,240 to 3,620 psi, ASA Green from 3,530 to 4,520 psi, PolyJet VeroCyan RGD843 from 7,350 to 7,900 psi, and Nylon12CF from 9,720 to 10,780 psi. It was not conclusive to pinpoint any flat orientation was stronger than the others. The upright orientation again showed the lowest strength among the four orientations. The decrease in strength in the upright orientation was very large in comparison with those of the other three flat orientations. Tensile strength of PolyJet VeroCyan RGD843 dropped from the range of 7,350 to 7,900 psi in flat orientations to 1,056 psi in upright orientation.

Figure 10 depicts modulus of elasticity of the thermoplastics. Orientation effects were not observed in ASA White and ASA Green materials. The modulus of elasticity of the two materials were relatively equivalent to each other. The modulus of ASA White varied from 184,467 to 208,700 psi/in., while those of ASA Green from 178,253 to 209,190 psi/in. The modulus of elasticity of ABS, PolyJet VeroCyan RGD843, and Nylon12CF demonstrated a very low value for the upright orientation, while the orientations of flat 0°, flat 45°, and flat 90° showed similar modulus values ranging from 82,760 to 107,180 psi/in. of ABS, from 273,965 to 292,844 psi/in. of PolyJet, and from 384,932 to 479,139 psi/in. of Nylon12CF. The modulus of elasticity was generally increasing from ABS, ASA White, ASA Green, PolyJet VeroCyan RGD843, to Nylon12CF.

Figure 11 shows rupture strength of the thermoplastics. Rupture strengths were relatively similar in the orientations of flat 0°, flat 45°, and flat 90° in ASA White, ASA Green, PolyJet VeroCyan RGD843, and Nylon12CF. The rupture strength of ABS at flat 45° was 415 psi. Those of ASA White ranged from 2,292 to 3,247 psi, ASA Green from 3,119 to 4,170 psi, PolyJet VeroCyan RGD843 from 6,392 to 6,494 psi, Nylon12CF from 9,486 to 10,759 psi. Very large drop in rupture strength were noted in ASA White, ASA Green, and Nylon12CF at upright orientation. The rupture strength was generally increasing from ABS, ASA White, ASA Green, PolyJet VeroCyan RGD843, and Nylon12CF materials.

Figure 12 depicts elongation at break of the thermoplastics. ABS demonstrated the lowest elongation at break among the group, although data at 45-degree orientation could only be obtained. Elongations of ASA White and Nylon12CF were similar, as ASA White values ranged from 0.114 to 0.135 inch and Nylon12CF values from 0.103 to 0.154 inch. ASA Green and PolyJet VeroCyan RGD843 demonstrated the next higher levels of elongation ranging from 0.15 to 0.265 inch in ASA Green and from 0.16 to 0.1975 inch in PolyJet VeroCyan RGD843. ABS demonstrated a highly brittle behavior among all thermoplastics.

Due to the brittle nature of the printed thermoplastics, lateral stains of all materials were very small and close to zero. Poisson's ratio, which is the ratio of lateral strain to tensile strain, was therefore approximately zero for all printed thermoplastics of the current study.

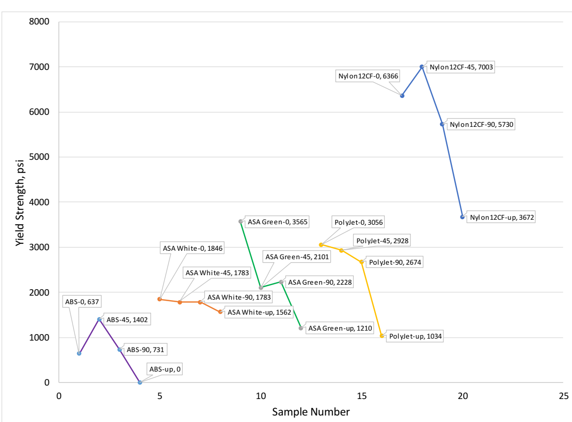

Figure 8. Yield Strength of Thermoplastics

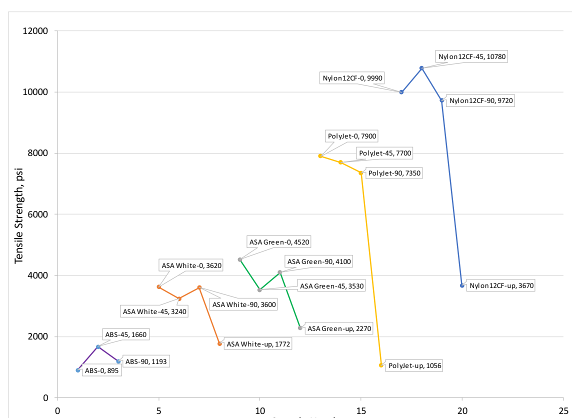

Figure 9. Tensile Strength of Thermoplastics

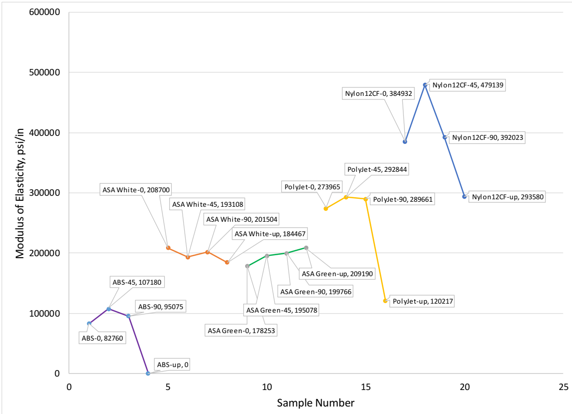

Figure 10. Modulus of Elasticity of Thermoplastics

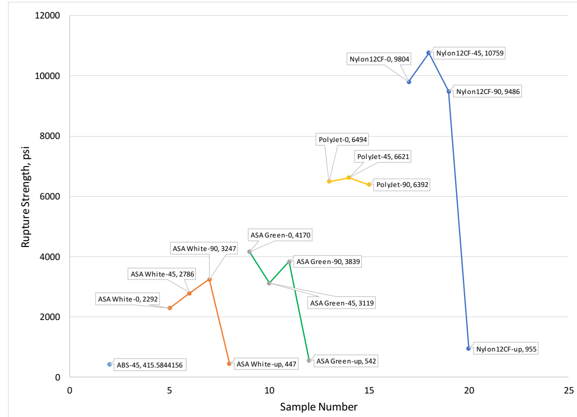

Figure 11. Rupture Strength of Thermoplastics

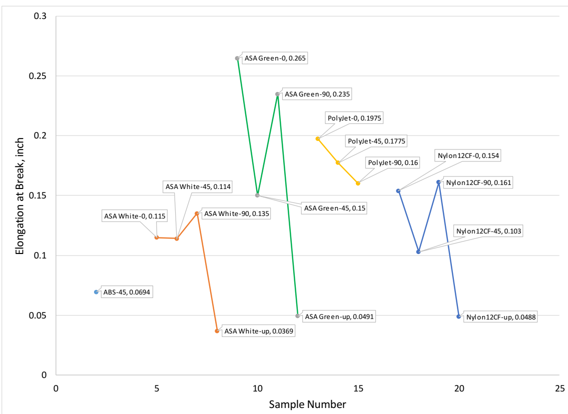

Figure 12. Elongation at Break of Thermoplastics

ABS microstructure took the form of honeycomb with strands of thermoplastics. Figure 13 and 14 show microstructures of flat 0° orientation and flat 45° orientation, respectively. Large amounts of porosity were found in ABS printed at flat 0° (Figure 15) than that at flat 45° (Figure 16). The porosity in ABS flat 0° resulted in lower yield strength (Figure 8) and lower tensile strength (Figure 9) in comparison with ABS flat 45°. Figure 17 shows the failure mode of ABS. A crack propagated from lower right to upper left covering approximately 80% of the cross-sectional area of a strand before fracture occurred.

ASA White was made up of strands of printed thermoplastics (Figure 18). The structure was filled with larger spherical porosity (Figure 19) in comparison with that in ABS. The material failed by a wide spread of crack initiation and propagation across all cross-sectional surfaces (Figure 20).

PolyJet VeroCyan RGD843 had a dense structure (Figure 21). Porosity was not observed. Due to the dense structure, tensile strengths of PolyJet VeroCyan RGD843 were higher than those of ABS, ASA White, and ASA Green (Figure 9). Yield strengths of PolyJet VeroCyan RGD843 were comparable to those of ASA Green. Nevertheless, they were generally higher than those of ABS and ASA White (Figure 8), thus PolyJet VeroCyan RGD843 therefore underwent a larger plastic deformation than the other two materials. PolyJet VeroCyan RGD843 failed by crack initiation at a point of outside surface (Figure 21) and the cracks propagated at all directions to fracture (Figure 22).

Nylon12CF consisted of a matrix of nylon strands impregnated with carbon fibers (Figure 23). Porosity was obtained in regions between nylon matrix and carbon fibers (Figure 24). The material failed by fracturing at the carbon fiber strands (Figure 25).

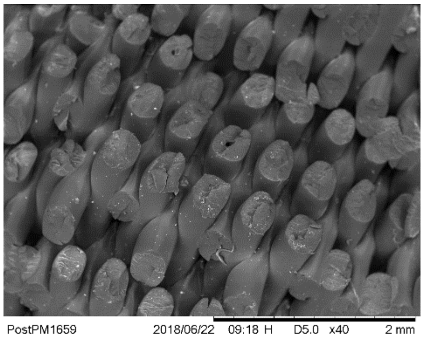

Figure 13. ABS at 0°, 40X

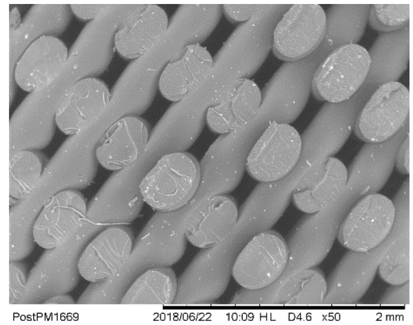

Figure 14. ABS at 45°, 50X

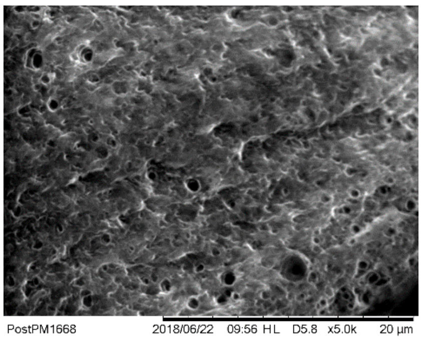

Figure 15. ABS at flat 0°, 5000X

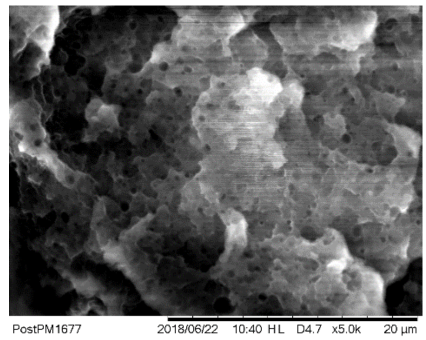

Figure 16. ABS at flat 45°, 5000X

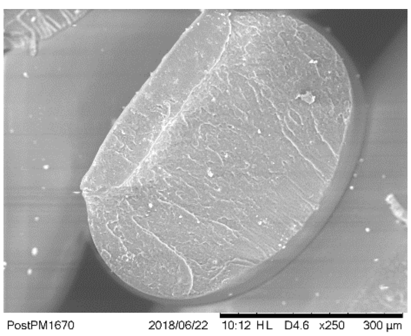

Figure 17. ABS at flat 45°, 250X

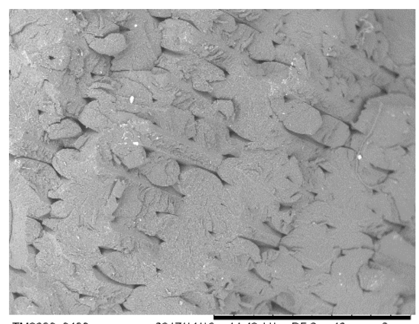

Figure 18. ASA White at flat 0°, 40X

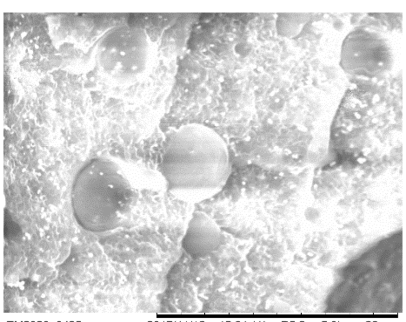

Figure 19. ASA White at flat 0°, 5000X

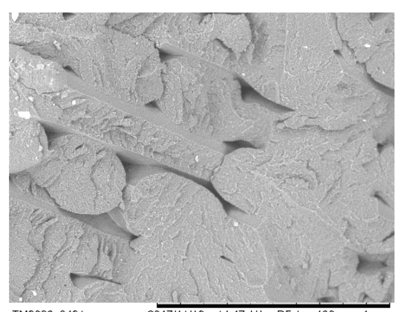

Figure 20. ASA White at flat 0°, 100X

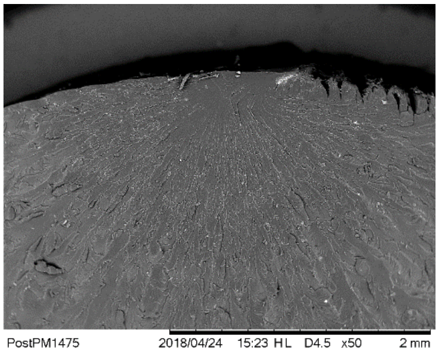

Figure 21. PolyJet VeroCyan RGD843 at flat 45°, 50X

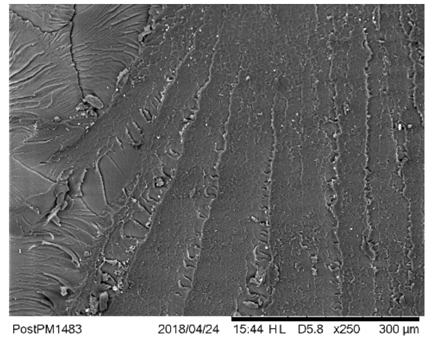

Figure 22. PolyJet VeroCyan RGD843 at flat 45°, 250X

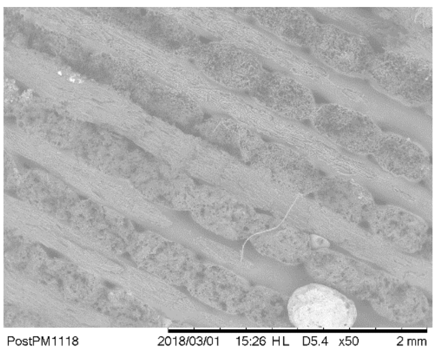

Figure 23. Nylon12CF at flat 45°, 50X

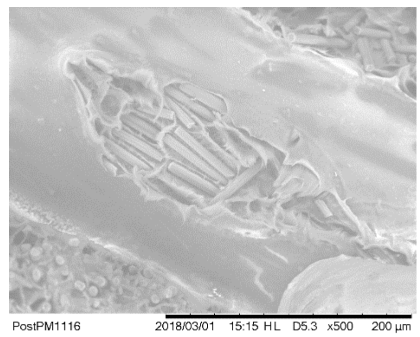

Figure 24. Nylon12CF at flat 45°, 500X

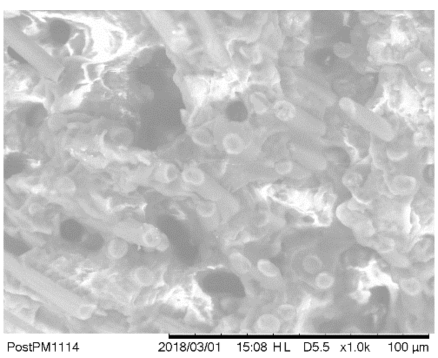

Figure 25. Nylon12CF at flat 45°, 1000X

4. CONCLUSIONS

Thermoplastic materials of ABS, ASA White, ASA Green, PolyJet VeroCyan RGD843, and Nylon12CF produced by 3D printers were investigated to determine their mechanical properties by tensile testing and microstructures by scanning electronic microscopy. The thermoplastic materials were of brittle nature, but they exhibited both elastic and plastic deformation behaviors. Printing orientations of flat 0°, flat 45°, and flat 90° had insignificant effects on mechanical properties in all materials. Printing orientation of upright diminished greatly yield strength and tensile strength, because materials separated easily between printing layers. Porosity played a vital role in determination of mechanical strength of thermoplastic materials. ABS with highest amount porosity due to its printed structure was much weaker than the dense PolyJet VeroCyan RGD843 materials. Nylon12CF, which was reinforced with carbon fibers, is the strongest material, but it fractured with little elongation. The Nylon12CF was a brittle and strong material. FDM printing process printed structures with porosity, while PolyJet printing process produced structures with high density. Printed materials produced by FDM are therefore weaker than those created by PolyJet. Reinforcement with carbon fibers enhanced mechanical strengths in materials printed by the FDM process. Mechanical properties of Nylon12CF reinforced by carbon fibers and produced by FDM process were generally stronger than those of PolyJet VeroCyan RGD843 produced by PolyJet process. Mechanical properties ranked from the lowest of ABS, ASA White, ASA Green, PolyJet VeroCyan RGD843, to the highest of Nylon12CF materials. The ranking was based on the properties of yield strength, tensile strength, rupture strength, and modulus of elasticity.

ACKNOWLEDGEMENTS
This study was supported by PSC-CUNY Research Award #60353-0048 and the Engineering Technology Department of Queensborough Community College in Bayside, New York. The authors are grateful to Professor Hamid Namdar, department chairman, Professor Stuart Asser, former department chairman, and Professor Edward Davis, and Mr. Jerry Sitbon for their supports, encouragement, and guidance. The authors would like to give many special thanks to Dr. David M. Sarno of the Chemistry Department of Queensborough Community College for providing the scanning electronic microscope and performing the SEM work.

REFERENCES
[1] B. Thompson, How 3D Printing Will Impact The Manufacturing Industry. *Manufacturing Business Technology* 01/19/2016.
[2] N. Sankar, K. Natarayan, G. Iyer, A. Kalathil, Printing the Future: From Prototypr to Production. *Cognizant 20-20 Insights*, November 2015, 1–8.
[3] T. Letcher, M. Waytashek, Material Property Testing of 3D-Printed Specimen in PLA on an Entry-Level 3D Printer, *ASME IMECE 2014 Proceedings*, Montreal, Canada, IMECE2014-39379.
[4] B. M. Tymrak, M. Kreiger, J. M. Pearce, Mechanical Properties of Components Fabricated with Open-Source 3-D Printers Under Realistic Environmental Conditions, *Materials & Design*, 58, (2014), 242-246.
[5] B. Rankouhi, S. Javadpour, F. Delfanian, T. Letcher, Failure Analysis and Mechanical Characterization of 3D Printed ABS With Respect to Layer Thickness and Orientation, *Journal of Failure Analysis and Prevention*, June 2016, Volume 16, Issue 3, 467-481.