Impact of Temperature and Material Variation on Mechanical Properties of Parts Fabricated with Fused Deposition Modelling (FDM) Additive Manufacturing

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Research Article

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Abstract

Additive Manufacturing (AM) can be deployed for space exploration purposes, such as fabricating different components of robots' bodies. The produced AM parts should have desirable thermal and mechanical properties to withstand the extreme environmental conditions, including the severe temperature variations on moon or other planets which cause changes in parts' strengths and may fail their operation. Therefore, the correlation between operational temperature and mechanical properties of AM fabricated parts should be evaluated. In this study, three different types of polymers, including polylactic acid (PLA), polyethylene terephthalate glycol (PETG), and acrylonitrile butadiene styrene (ABS), were used in Fused Deposition Modeling (FDM) process to fabricate several parts. The mechanical properties of produced parts were then investigated at various temperatures to generate knowledge on the correlation between temperature and type of material. When varying the operational temperature during tensile tests, the material's glass transition temperature was found influential in determining the type of material failure. Among the materials used, ABS showed the best mechanical properties at all temperatures due to its highest glass transition temperatures. The results of statistical analysis indicated the temperature as the significant factor on tensile strength while the type of material was not a significant factor.

1. Introduction

The advent of Additive Manufacturing (AM) has revolutionized the part production methods [1][2]. While in conventional manufacturing methods the raw material should undergo several different manufacturing steps, such as forming, machining, welding, etc. [3][4], AM can produce the components in a layer-based single step fabrication process [5] with desirable mechanical properties [6][7][8]. Depending on the format of material feedstock, which can be powder, foil, paste, etc., the material feeding method to the AM process can be different [9][10]. In powder-based AM methods, powder spreadability dominates the material feeding process to the AM system [11], while in the Fused Deposition Modeling (FDM) process the ability to extrude polymer material to the AM system is a role-player [12].

The AM and its related developments, defects, and downsides have been studied in the literature in the recent past years. A novel technique for analyzing the in-situ 3D transient thermal variations in powder-bed AM processes was developed by Lazoglu et al. [13][14]. This advanced model could track the material phases, porosity, and thermal properties, especially instantaneous transient temperature fields following the variations in time and laser path. This model can be very useful in fabrication of conductive tracks, resistors, electrodes, and heating elements using AM methods; such parts were produced by printing selectively distributed conductive and insulating locations per layer [15]; using the direct ink writing AM process, complex-geometry parts were printed with a feedstock mixture of carboxymethyl cellulose and graphite particles. Some solutions to avoid the defect of staircase effects on shell and solid components were proposed in [16]; they printed the material in a varied intra-layer thicknesses by utilizing an advanced multi-axis path planning model; the implemented efficient toolpaths aided in adjusting the form of top surface and keeping a high-quality part. In another work by the same group [17], a nonplanar

helical slicing method was developed to create a single continuous 3D tool path (compared with 2.5D planar methods) with the goal of eliminating seam defects. The developed system benefited from a simplified extruder control without extra movements. In addition, a novel slicing method of the CAD model was used to fabricate spherical parts [18]; while conventionally the CAD model is sliced into planes, the proposed method innovatively sliced the CAD model into spherical shells, where the tool paths are guided to deposit the spherical layers. In addition to these defects, a disadvantage of AM is the high waste of material for production of complex-geometry parts composed of large overhangs, where filling the space between the overhang and the build plate is required. While conventional in-situ printing of support structures was useful in fabricating the parts with desirable dimensional accuracy, their removal post-processing was a waste of time and material. A solution to this downside was proposed in [19][20][21], where an already produced reusable modular support considerably decreased the need for printing the in-situ support structures, reduced the material usage, and shortened the fabrication time. The modular support itself can be fabricated using the AM methods to meet the required complexity in their geometries [22].

In FDM process, following the part geometry data, the nozzle extrudes the polymer filament onto the build plate for the first part's layer [23]. Then, either the extruder or build plate moves to create the gap for the next layer. After that, the extruder prints the next layer on the previous layer. By repetition of this process, the final part is fabricated [24]. The FDM process parameters are build orientation, layer thickness, raster angle, extrusion temperature, and infill density [25]. These process parameters should be adjusted in a way that each printed track could be properly bounded to the side tracks and previous printed layer [26][27].

One of the important applications of AM is in space exploration since it provides the benefit of part fabrication in just a single step [28]. Also, the rapid production of spare parts for exploration robots on the moon or other planets is another advantage of AM deployment in space exploration purposes [29]. Several components of robot's bodies should be fabricated in light weight but high strength to both use low amount of energy and properly perform the tasks. Polymers can be used to fabricate parts with light weights although the environmental conditions can considerably influence their mechanical properties [30]. The tensile properties, for instance, can be significantly affected by the variation in temperature [31]. At high temperatures the material may behave like a ductile material while at low temperatures the same material may show brittle performance [32]. Thus, for designing the components that operate in extreme thermal conditions, the relation between type of material, environmental conditions, and mechanical properties should be evaluated. Even the surface coating can have significant effects, as found in a work by Lazoglu et al. [33], where the impact of spray coating on the PLA parts fabricated by FDM was studied; although the coating didn't improve the tensile strengths, it considerably increased the samples' elongation.

In this study, the relation between thermal operational conditions and mechanical properties have been investigated. The parts were fabricated with three types of polymer, including polyethylene terephthalate glycol (PETG), polylactic acid (PLA), and acrylonitrile butadiene styrene (ABS). The parts were produced

using FDM method. The statistical analysis was conducted on the results to determine the significant factors and their influence on mechanical properties.

2. Materials And Methods

Filaments of three thermoplastic materials, PETG, PLA, and ABS with filament diameter 1.75 mm were provided and their properties are shown in Table 1. The tensile coupons were loaded into the tensile testing machine, where they were pulled to breaking. Upon completion of these tests, the results were analyzed and material properties such as ultimate tensile strength (UTS) and modulus of elasticity (E) were determined. Tests were conducted according to ASTM D638 [34][35], except when modified in a few key areas. The tensile coupons were modified to promote consistent fracturing in the neck of the sample. Coupon neck widths were decreased from the ASTM standard, and the fillet from the grip to the neck was increased in both length and diameter. The modification stemmed from other research, showing this type of modification to improve the behavior of 3D printed tensile coupons under test [36]. The tensile testing machine used was an Instron 5969 outfitted with a 10 kN load cell [37]. The strain rate used was 5 1/min, which is the minimum speed recommended in ASTM D638. The jaws utilized for this experiment were flat jaws with a maximum capacity of 50 kN. The jaws were tightened until snug then an additional ¼ turn was added to make sure the samples did not slip during the test. The machine set-up can be seen in Figure 1.

Table 1
The properties of polymers used in this study

Material	Glass transition temperature (°F)	Ultimate tensile strength (psi)
PETG	176	7079
PLA	140	7964
ABS	221	5872

The tensile test samples were fabricated using a Prusa i3 printer. The used process parameters were 100% infill density (to eliminate interactions with infill patterns), 0.2 mm layer thickness, 30 mm/s printing speed, and 0.5 mm nozzle diameter. The samples were printed at a 45° angle on the print bed to ensure a majority of the layers were printed along the length of the part instead of at 45°. Finally, to prevent the crack propagation from the start or stop of the printer at the layer transition, it was made sure that the start and stop of each layer did not lie within the neck of the coupon. All of these specifications were kept constant for all of the samples. Figure 2 shows an instance of a printed tensile coupon of PLA.

The temperature was varied at three different levels of 40, 65, and 170°F to assess its impact on mechanical properties. For providing the 170°F (hot) operational temperature, the samples were immersed in hot water at 170°F until they reached a steady state temperature of 170°F. These samples were then rapidly removed out of hot water with warm pliers and inserted into the tensile testing machine. A heat gun was used to create a warm environment around the sample and keep it at steady state

temperature to limit heat transfer. For providing the 40°F (cold) operational temperature, the cold samples were brought down to 40°F while soaking in an ice-bath. To prevent moisture absorption into the material, samples were placed into a plastic bag before being soaked in the ice-bath. These samples were then removed from the cooler with cold pliers and inserted into the tensile testing machine. The temperature was verified with a FLIR thermal imaging camera during each test, an instance of which is shown in Figure 3. For the room temperature samples the room temperature was gathered before and during the testing to verify that it was kept constant; the lab’s temperature was constant at 65°F throughout the test.

3. Results And Discussion

3.1. PETG

In order to determine the stress and strain of the various samples, the width, thickness, and gauge length of the tensile coupons were recorded. The gauge length of the tensile testing machine was set to 3.9 inches to keep it consistent among all materials and temperatures tested. The thickness, width, and the obtained UTS of the hot PETG samples are shown in Table 2.

Table 2
Dimensions and tensile strengths of hot PETG test coupons

Sample #	Width (in)	Thickness (in)	UTS (psi)
1	0.245	0.195	2619
2	0.247	0.199	2373
3	0.246	0.199	1776
4	0.245	0.194	2175
5	0.243	0.193	2127

The hot PETG samples after the tensile testing are shown in Figure 4. The hot PETG samples were tested until the UTS was reached, except sample #5 that went out of control and was fully separated. The PETG material behaved as a ductile material at the raised temperature (170°F). The samples show the necking phenomenon same as ductile materials. Since 170°F is roughly 5% less than the glass transition temperature of PETG, which is 176°F, the inaccuracies of heating the samples with the heat gun could have led to the material passing the glass transition temperature. This resulted in the samples elongating more than the rest of the samples tested in this experiment. This finding suggests that the material behavior is in the glass transition state as it is neither brittle nor rubbery.

The thickness, width, and the obtained UTS of the cold PETG samples are shown in Table 3. The cold PETG samples as seen in Figure 5, were tested until fracture. The samples acted as a brittle material because the samples’ temperature (40°F) was 88% less than the glass transition temperature (176°F). This indicated that the material behaved in the glassy state.

Table 3
Dimensions and tensile strengths of cold PETG test coupons

Sample #	Width (in)	Thickness (in)	UTS (psi)
1	0.250	0.190	6408
2	0.249	0.195	6222
3	0.249	0.197	6628
4	0.250	0.197	6486
5	0.249	0.192	6706

The thickness, width, and the obtained UTS of the room temperature PETG samples are shown in Table 4. The room temperature PETG samples, as shown in Figure 6, resulted in a brittle fracture. This is because the material was still below the glass transition temperature in the glassy state.

Table 4
Dimensions and tensile strengths of room temperature PETG test coupons

Sample #	Width (in)	Thickness (in)	UTS (psi)
1	0.251	0.200	6741
2	0.251	0.200	6567
3	0.249	0.198	6066
4	0.251	0.198	6363
5	0.251	0.200	6626

The stress-strain graphs were developed with the results obtained from the tensile testing machine. The 5 samples of each temperature were averaged and plotted on the graph seen in Figure 7. The stiffness can also be qualitatively observed, where a steeper stress-strain curve slope indicates a stiffer material. The summary of the mean UTS and E of PETG at different temperatures is shown in Table 5.

Table 5
Summary of mechanical properties for PETG samples

Test Temperature (°F)	Average UTS (psi)	Average E (psi)
40	6429	270,225
65	6140	292,027
170	1998	169,894

3.2. PLA

The hot PLA test did not conclude with any useful data within the scope of this experiment. The PLA's glass transition temperature is 140°F, which is roughly 20% lower than the 170°F temperature used in this experiment. This made the PLA samples within the rubbery state of the material. The first test of hot PLA samples took less than the preload force to make it yield. The stress-strain curve of these samples would have been a graph with a constant zero result.

The thickness, width, and UTS of the cold PLA samples can be seen in Table 6. The cold PLA samples as shown in Figure 8, were tested until fracture. The samples acted as a brittle material since the samples' temperature was 72% less than the glass transition temperature, indicating that they perform in the glassy state.

Table 6
Dimensions and tensile strengths of cold PLA test coupons

Sample #	Width (in)	Thickness (in)	UTS (psi)
1	0.243	0.207	7664
2	0.242	0.206	7751
3	0.249	0.210	7734
4	0.243	0.207	7888
5	0.243	0.210	7832

The thickness, width, and UTS of the room temperature PLA samples can be seen in Table 7. The room temperature PLA samples as shown in Figure 9, resulted in brittle fracture, i.e., these samples were still in the glassy state at roughly 46% of the glass transition temperature.

Table 7
Dimensions and tensile strengths of room temperature PLA test coupons

Sample #	Width (in)	Thickness (in)	UTS (psi)
1	0.242	0.207	7209
2	0.243	0.207	7241
3	0.243	0.207	7218
4	0.242	0.207	7166
5	0.244	0.208	7335

The stress-strain graphs were developed with the results obtained from the tensile testing machine. The 5 samples of each temperature were averaged and plotted on the graph shown in Figure 7.

The summary of the mean UTS and E of PLA at different temperatures is shown in Table 5.

Table 8
Summary of mechanical properties for PLA samples

Test Temperature (°F)	Average UTS (psi)	Average E (psi)
40	7761	431,666
65	7225	463,336

3.3. ABS

All ABS samples were successfully tested until fracture. The ABS tensile coupons exhibited signs of brittle failure at all temperatures. Out of all the materials tested, the failure mode of ABS was the most consistent across the tested temperature range. Due to its high glass transition temperature (221°F), the ABS samples remained closer to the glassy state while being tested at high temperatures. The thickness, width, and UTS of the hot ABS samples can be seen in Table 9. Hot temperature samples showed some signs of necking, shown in Figure 11, as lighter-colored regions of stretched material near the fracture, but mostly exhibited signs of brittle fracture.

Table 9
Dimensions and tensile strengths of hot ABS test coupons

Sample #	Width (in)	Thickness (in)	UTS (psi)
1	0.236	0.202	2473
2	0.234	0.202	2271
3	0.235	0.202	2508
4	0.236	0.203	2445
5	0.235	0.202	2508

The thickness, width, and UTS of the cold ABS samples can be seen in Table 10. The cold ABS samples as shown in Figure 12, were tested until fracture. The samples acted as a brittle material because the deployed temperature was 82% less than the glass transition temperature, indicating that the material was in the glassy state.

Table 10
Dimensions and tensile strengths of cold ABS test coupons

Sample #	Width (in)	Thickness (in)	UTS (psi)
1	0.246	0.201	5473
2	0.248	0.203	5760
3	0.245	0.199	5624
4	0.238	0.199	5183
5	0.247	0.200	5422

The thickness, width, and UTS of the room temperature ABS samples can be seen in Table 11. The room temperature ABS samples as seen in Figure 13, resulted in brittle fractures as these samples were still in the glassy state at roughly 29% of the glass transition temperature.

Table 11
Dimensions and tensile strengths of room temperature ABS test coupons

Sample #	Width (in)	Thickness (in)	UTS (psi)
1	0.242	0.203	4497
2	0.244	0.202	5010
3	0.236	0.202	4988
4	0.243	0.202	5031
5	0.245	0.200	5258

The stress-strain graphs were developed with the results obtained from the tensile testing machine. The 5 samples of each temperature were averaged and plotted on the graph shown in Figure 14.

The summary of the mean UTS and E of ABS at different temperatures is shown in Table 12.

Table 12
Summary of mechanical properties for ABS samples

Test Temperature (°F)	Average UTS (psi)	Average E (psi)
40	5473	357,714
65	4902	369,968
170	2415	261,100

3.4. Statistical Analysis

The powerful statistical commercial software of JMP [38] was used to conduct statistical analysis to evaluate the results. The data collected was analyzed using factorial statistical design. The 2 variable factors are type of material and temperature. The type of material has 3 levels of PETG, PLA, and ABS, and the temperature has 3 levels of 170, 65, and 40°F. The response variable was considered as UTS. The design of experiment can be denoted as a 3^2 factorial, with 9 different test combinations. Each test condition was replicated 5 times, i.e., total of 45 tensile tests were performed. The data used for analysis is provided in Table 13, which shows the UTS for various materials and temperatures. By performing analysis of variance (ANOVA) on this data, the combination of best material and temperature will be statistically determined, by considering that the higher strength and modulus is desired.

Table 13
Test combinations for statistical analysis

Temperature (°F)	Material	UTS (psi)
170	PETG	2619
170	PETG	2373
170	PETG	1776
170	PETG	2175
170	PETG	2127
40	PETG	6408
40	PETG	6222
40	PETG	6628
40	PETG	6486
40	PETG	6706
65	PETG	6741
65	PETG	6567
65	PETG	6066
65	PETG	6363
65	PETG	6626
170	PLA	0
170	PLA	0
170	PLA	0
170	PLA	0
170	PLA	0
40	PLA	7664
40	PLA	7751
40	PLA	7734
40	PLA	7888
40	PLA	7832
65	PLA	7209
65	PLA	7241

Temperature (°F)	Material	UTS (psi)
65	PLA	7218
65	PLA	7166
65	PLA	7335
170	ABS	2473
170	ABS	2271
170	ABS	2508
170	ABS	2445
170	ABS	2508
40	ABS	5473
40	ABS	5760
40	ABS	5624
40	ABS	5183
40	ABS	5422
65	ABS	4497
65	ABS	5010
65	ABS	4988
65	ABS	5031
65	ABS	5258

The results of a two-way ANOVA with significance level 5% are shown in Table 14. The P-value for this experiment was found 0.002. Thus, it is concluded that the UTS results of combinations of material and temperature are statistically significant different.

Table 14. Results of ANOVA generated by JMP Software

Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	105616419	21123284	4.6579
Error	39	176862039	4534924.1	Prob > F
C. Total	44	282478458		0.0020*

The results of main effect tests and their interaction are shown in Table 15. Considering the significance level of 5%, the interaction term was not statistically significant (P-value 0.1903). Considering the main effects, the type of material was not a significant factor (P-value 0.5556) while the temperature was a significant factor (P-value 0.0001). The temperature variable contributed significantly to the change in ultimate strength. The material of the sample had less effect on the change in strength, particularly at room temperature. This can also be noted by the behavior of the confidence curves; the confidence curve crosses the horizontal residual line in Figure 15, so the effect of temperature is significant. The confidence curves do not display this behavior in Figure 16 and Figure 17, so the effects of material and interaction term (temperature-material) are not significant.

Table 15. The results of main effect tests and their interaction

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Temperature	1	1	84497989	18.6327	0.0001*
Material	2	2	5410872	0.5966	0.5556
Temperature*Material	2	2	15707559	1.7318	0.1903

4. Conclusion

In this study, the impact of temperature on mechanical properties of polymers fabricated with Fused Deposition Modeling (FDM) was investigated. Three types of thermoplastic polymers, including polylactic acid (PLA), polyethylene terephthalate glycol (PETG), and acrylonitrile butadiene styrene (ABS) were used to fabricate tensile coupons. The tensile tests were performed at three temperatures of 40, 65, and 170°F. The JMP program was used to statistically analyze the results. It was found that the temperature was the significant factor while neither the type of material nor the interaction term (temperature-material) had any significant effects on tensile strengths. At elevated temperatures, ABS maintained greater strength and stiffness than PLA and PETG. At lower temperatures, ABS is not as strong by either measure; however, parts can be designed to account for the lower yield strength and stiffness, while it is significantly more difficult to design a part to handle the effects of extreme temperature.

5. Declarations

a. Funding

No funds, grants, or other support was received.

b. Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest.

c. Availability of data and material

The raw/processed data required to reproduce these findings will be made available on request.

d. Code availability

Not applicable

Compliance with ethical standards

e. Ethics approval

The manuscript contains original ideas which have never been published before in other journals.

f. Consent to participate

This study is not a human transplantation study. No consent needed for this paper.

g. Consent for publication

The authors declare their consent for publication.

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Figures

Figure 1

An instance of tensile testing setup used for characterization of mechanical properties.

Figure 2

An instance of a printed tensile coupon of PLA.

Figure 3

FLIR images of (a) hot (170°F), and (b) cold (40°F) tensile samples.

Figure 4

Hot temperature (170°F) PETG samples after tensile testing.

Figure 5

Cold temperature (40°F) PETG samples after tensile testing.

Figure 6

Room temperature (65°F) PETG samples after tensile testing.

Figure 7

The stress-strain curve for PETG samples at different temperatures.

Figure 8

Cold (40°F) PLA samples after tensile testing.

Figure 9

Room temperature (65°F) PLA samples after tensile testing.

Figure 10

The stress-strain curve for PLA samples at different temperatures.

Figure 11

Hot (170°F) ABS samples after tensile testing.

Figure 12

Cold (40°F) ABS samples after tensile testing.

Figure 13

Room temperature (65°F) ABS samples after tensile testing.

Figure 14

The stress-strain curve for ABS samples at different temperatures.

Figure 15

The confidence curve for effect of temperature on UTS.

Figure 16

The confidence curve for effect of material on UTS.

Figure 17

The confidence curve for effect of interaction term (temperature-material) on UTS.