EXPLORING VARIABILITY IN MATERIAL PROPERTIES OF MULTI-MATERIAL JETTING PARTS

Lindsey B. Bass, Nicholas A. Meisel, and Christopher B. Williams
Design, Research, and Education for Additive Manufacturing Systems Laboratory
Department of Mechanical Engineering, Virginia Tech

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ABSTRACT

With Additive Manufacturing (AM) capabilities rapidly expanding in industrial applications, there exists a need to quantify materials' mechanical properties to ensure reliable performance that is robust to variations in environment and build orientation. While prior research has examined process-parameter and environmental effects for AM processes such as extrusion, vat photopolymerization, and powder bed fusion, existing similar research on the material jetting process is limited. Focusing on polypropylene-like (VeroWhitePlus) and elastomer-like (TangoBlackPlus) materials, the authors first characterize the anisotropic properties of six different gradients produced from mixing the two materials in preset quantities. Three build orientations were used to fabricate parts and analyze tensile stress, modulus of elasticity, and elongation at break for each material. The authors also present results from an investigation of how aging of parts in different lighting conditions affects material properties. The results from these experiments provide an enhanced understanding of the material behaviors relating to material jetting process parameters and can inform material selection when manufacturing load-bearing parts.

1. INTRODUCTION

Additive Manufacturing (AM) is quickly evolving from a method for prototyping to a desired alternative for manufacturing end-use products. Because of the nature of a layer-by-layer fabrication process, customizable artifacts are achievable that save material, time, and cost compared to traditionally-manufactured parts. In particular, the material jetting process works by selectively depositing droplets of build material to form parts [1]. An example is the PolyJet material jetting system commercialized by Stratasys [2] that is capable of simultaneous deposition of multiple photopolymer resins. In the PolyJet process, a print block consisting of the inkjet heads deposits the support or build materials in drop-by-drop deposition patterns, which are smoothed by a roller and cured by a UV lamp (Figure 1).

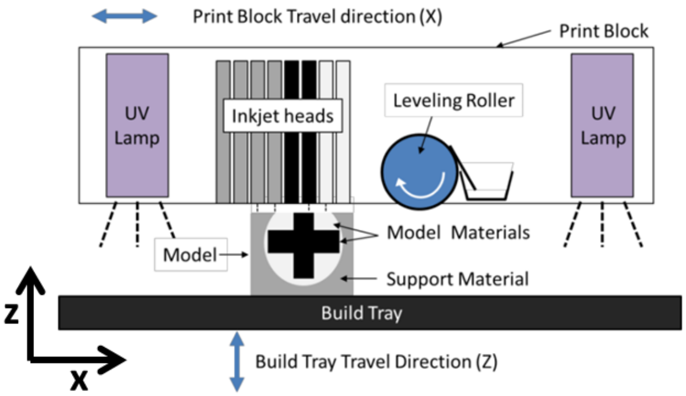


Figure 1. Representation of the PolyJet Printing Process

While material jetting processes, such as the PolyJet process, offer unique multi-material capabilities, research is still needed to identify the impact that process variations have on the quality of the final manufactured part. For example, this style of layer deposition can introduce build defects and inconsistencies due to how the material droplets are spread and bond. In order to ensure that load-bearing, end-use, material-jetted products meet the required specifications (which could include having high ultimate tensile stress, directionally-independent ultimate tensile stress, or strength longevity), variations in the material properties must be examined.

In this paper, two common materials for the Stratasys Objet350 Connex were studied: a polypropylene-like material, VeroWhitePlus (VW+), and an elastomer-like material, TangoBlackPlus (TB+), as well as gradients produced from drop-by-drop dithering patterns of the materials. To identify variations in these digital materials, mechanical properties were investigated with respect to build orientation and part age, two key factors that have the potential to significantly affect tensile stress, elastic modulus, and elongation at break.

Related research has been divided into three parts. Section 1.1 outlines the main contributors to orientation effects in various AM technologies. Since each fabrication process is different, material properties are also expected to differ. In Section 1.2, advances in the material jetting process are noted, and these findings guided the direction of this experiment. Section 1.3 transitions to aging effects, which is currently limited in literature for AM photopolymer materials; however, the vat photopolymerization findings are important to consider and should be compared to the material behaviors witnessed in this material jetting study.

1.1 *Anisotropy in AM*

Existing literature has explored the effects of orientation on mechanical properties for multiple AM processes. Kotlinski offers a review comparing AM materials with an extensive list of mechanical properties [3]. Among powder bed fusion, material extrusion, binder jetting, vat photopolymerization, sheet lamination, and material jetting technologies, anisotropic effects exist, but are shown to differ. Puebla and coauthors investigated orientation with vat photopolymerization and found that the specimens built flat on the build plane had significantly lower ultimate tensile stresses and elastic modulus values compared to parts built vertically or on an edge [4]. Lee and coauthors looked at multiple build orientations in the extrusion, binder jetting, and nano composite deposition system processes [5]. Binder jetting was the only method producing low axial compressive strength, and extrusion had the highest axial compressive strength. The compressive tests further confirmed that build direction is a significant parameter affecting material properties. Zeleny and coauthors compared extrusion and material jetting with ABS plastic and an ABS-like material respectively [6]. Extrusion parts printed on their edges had higher tensile strengths than parts printed flat. Among the three orientations for the material jetting parts (flat parts printed along and perpendicular to the build direction and parts printed on their edge along the build direction), the tensile strengths more than doubled compared to extrusion parts. Flat parts printed perpendicular to the build direction had the highest tensile strength, while parts printed on an edge had the lowest.

1.2 *Orientation Effects in Material Jetting*

Concerning studies solely focusing on the material jetting process, Pilipović and coauthors thoroughly explored a variety of mechanical properties of VeroBlack, VeroBlue, and FullCure

720 materials and found FullCure 720 to perform the best in maximal flexural strength [7]. Similarly, Singh and Singh compared three jetted materials and were able to determine that VeroWhite material fabricated horizontally compared to at 45- or 90-degree angles with the build bed was the most dimensionally-accurate and cost-effective material as opposed to VeroBlue and Fullcure 720 [8]. Blanco and coauthors also directly explored slant angles with strips printed in seven acute-angle orientations [9]. The relaxing modulus was highest at 0 and 90 degrees, and their trends revealed the potential for a shielding effect due to how the support material is UV-cured. Barclift and Williams used a design of experiments to test factors of XY-orientation (in the build plane) and Z-orientation (height direction) [10]. While they were unable to establish statistically significant trends in tensile strength and tensile modulus pertaining to orientation, their work highlights how Z-orientation can affect the dimensional accuracy of a part produced via material jetting. Adamczak and coauthors analyzed three orientations of VeroWhite material and discovered anisotropy although averaged ultimate tensile stress values were similar across orientations [11]. Vertical pieces, however, were found to be the most brittle. Using FullCure 720, Kesy and Kotlinski also witnessed an anisotropic trend but with different findings: parts oriented with the longest dimension along the build direction and second longest along the Z-axis were the strongest parts, parts oriented vertically were next strongest, and the weakest were parts with the longest dimension along the build direction and the second longest perpendicular to the build direction in the build plane [12].

Orientation results in prior literature clearly differ by AM process: while flat parts had lowest ultimate tensile stresses in vat photopolymerization, only edge-oriented extrusion parts experienced significantly higher ultimate tensile stresses. Material jetting research has often produced inconsistent anisotropic trends, but some tests have shown parts on their edge being strongest. Besides considering the build process differences, different materials do not maintain similar trends, which further emphasizes the difficulty of material characterization and the necessity for continued research. In this study, both VW+ and TB+ will be examined to learn about the behavior of rigid and flexible materials in multiple orientations and how (if at all) the mechanical properties vary. To the authors' knowledge, this is the first orientation analysis of digital materials involving TB+.

1.3 *Aging in Photopolymer AM Processes*

Aside from orientation, another important factor potentially affecting the strength of end-use AM parts is age. The vast majority of prior research into aging of AM parts is with the vat photopolymerization process. Tröger and coauthors investigated aging of multiple acrylate-based resins to more clearly understand the materials' behaviors as they apply to engineering and biological applications [13]. By considering thermal aging, humidity aging, and UV aging separately, the authors were able to determine that while aging mainly depended on the material, humidity caused swelling and a reduction in mechanical properties. Furthermore, higher temperatures and short wavelength light irradiation affected material color and mechanical properties. Ottemer and Colton examined epoxy-based resins in a seven-week study with four different relative humidity scenarios [14]. While aging did not yield significant trends in mechanical properties, specimens in the more humid environments noticeably absorbed water and deteriorated in strength. Using a 24-day aging cycle, Mansour and coauthors also used an epoxy resin and determined that as aging proceeds, the mechanical properties reach equilibrium after an improvement of tensile modulus, maximum tensile stress, flexural modulus, and strength

[15]. The percent elongation at break and impact strength were shown to decrease over time. Puebla and coauthors also took a look at aging, and they used 4-, 30-, and 120-day intervals for aging experiments. Results showed that the shortest time interval corresponded to the lowest ultimate tensile stresses. Humidity significantly reduced mechanical properties as did the longest aging cycle for one of three materials investigated [4].

The results from current literature fail to reach an agreement regarding one trend of mechanical property behavior over time. To the authors' knowledge, there is no research in aging behavior for the material jetting process. The authors have therefore chosen to focus on this process with VW+ material to make a valuable contribution to expanding knowledge on the evolution of mechanical properties with age.

1.4 *Context*

In this paper, the effects of orientation and aging are analyzed to determine the effect of material jetting process parameters on the mechanical properties of end-use parts. Three build orientations are explored among six photopolymer materials. In a separate investigation, one material is studied over 10 weeks, a length of time the authors felt could allow parts to set in order to yield changes in material behavior after many days. The analysis of the mechanical properties will provide knowledge about material characterization leading to a better understanding of the reliability of material-jetted end-use parts. Section 2 discusses the effect of build orientation on mechanical properties, and the effect of aging is analyzed in Section 3. Both of these sections begin with an outline of the experimental methods (Sections 2.1 and 3.1 respectively.) Sections 2.2 and 3.2 present the results of ultimate tensile stress, modulus of elasticity, and elongation at break. A summary of the key findings follows in Sections 2.3 and 3.3. Finally, the closure evaluates the achievements of this investigation as well as future considerations (Section 4).

2. EFFECT OF ORIENTATION

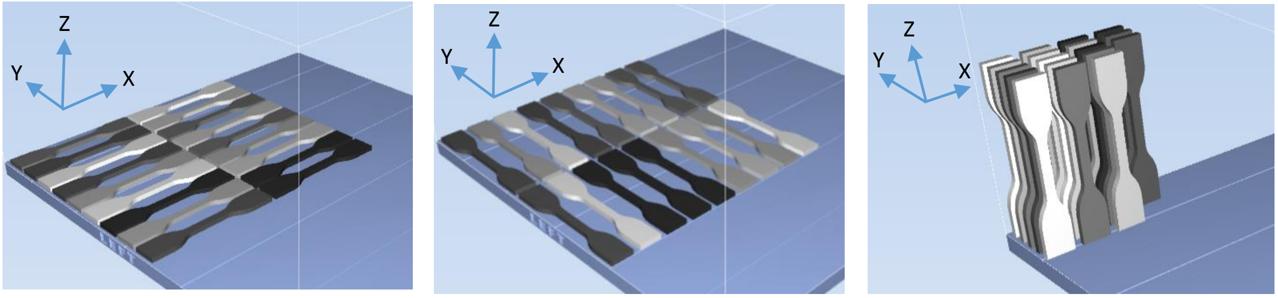
2.1 *Experimental Methods*

To better understand the material behavior of multi-material jetting parts, six different materials were investigated, each with different concentrations of VW+ and TB+ based on pre-arranged drop-by-drop dithering patterns. The materials are displayed in Table 1 along with abbreviations that will be used in this paper. VW+ is a rigid, polypropylene-like photopolymer material, while TB+ is a flexible, elastomer-like photopolymer material. The flexibility of the intermediate gradient materials is directly proportional to the percentage of TB+ material present in the printed composite. The experimentation in the following section is intended to explore variability in mechanical properties of six digital materials when they are built in different orientations.

Table 1. Range of Materials for the Study [16]

Material (Rigid)	Abbreviation	Material (Flexible)	Abbreviation
VeroWhitePlus	VW+	TangoBlackPlus_Shore85	TBS85
VeroGrey35	VG35	TangoBlackPlus_Shore60	TBS60
VeroGrey50	VG50	TangoBlackPlus	TB+

Using the ASTM D638 Type IV tensile specimen [17], mechanical properties of each digital material were evaluated for three different orientations. Three specimens were printed for each material and orientation under investigation. Figure 2a provides the configuration of parts oriented with their longest direction along the X-axis and their second-longest direction along the Y-axis, which will be referred to as XY-parts to conform to ASTM standards [18]. Parts with the longest dimension along the Y-axis and second-longest along the X-axis (YX-parts) are shown in Figure 2b, and Figure 2c presents the ZX-parts: parts with the longest dimension along the Z-axis and the second-longest along the X-axis. These three orientations were selected out of the six possible orientations to be representative of how each of the longest directions affects mechanical properties. Additionally, many sources ([4], [6], [9], [11], [12]) set up their samples with all three orientations on the same build tray, but this study separates orientation by tray to ensure there are uniform UV-curing effects across all specimens. When parts of different heights are placed on the same build tray, the UV irradiation has potential to over-cure parts adjacent to the current printing path [10], which could be the case on a tray with multiple orientations when only the vertical parts are still printing and while the top surfaces of the flat parts remain exposed for the remainder of the build.



(a) (b) (c)

Figure 2. Parts oriented on the build tray with various grayscales representing the different materials: a) XY-parts, b) YX-parts, and c) ZX-parts.

All specimens were arranged on the build tray using the automatic placement feature with locked orientations. Each tray had three specimens of each of the six materials, and materials were randomly assigned to their placement. In order to prevent the machine's vibrations or the print roller from causing undesired motion in the ZX-parts during printing, a roof-like structure consisting of a thin sheet of VW+ material was designed to be printed above the specimens. This forced the machine to fully support the specimens by fabricating the parts all within a solid block of support material. Without incorporating this strategy, the ZX-parts wobbled during the build and exhibited severe print defects in their upper regions.

Parts were printed in Digital Materials Mode (layer thickness of 32 microns) with matte finish. Following printing, all support material was removed via a high-pressured waterjet cleaning station. Surrounding conditions were maintained at an average of 72˚F and 27% humidity. Environmental conditions were maintained relatively consistent because of the potential for altered results from introducing temperature and humidity as additional variables. This has been observed with past experiments in humid environments where part strength was greatly diminished ([4], [13], [14]). To reduce potentially harmful effects from extended environmental exposure, parts were cleaned and tested immediately upon print completion.

The print block for the material jetting process, which is referenced in Figure 1, moves along the X-axis from left to right. The print pass rows are defined by the white lines parallel to the X-axis on the build trays in Figure 2. The authors hypothesized that this directional print process unique to the material jetting technology would cause material properties to be dependent on orientation. XY-parts were expected to be strongest since they are jetted along the direction of tensile strain. ZX-parts were predicted to be weakest since each deposited layer has small cross-sectional areas, creating the potential for delamination. Since the XY-plane has the lowest printing resolution, poor dimensional accuracy from the discretized nature of the jetted layer fabrication could also misalign layers along the Z-axis leading to premature failure [10].

Tensile testing was performed using the Instron 5984 Mechanical Testing Machine using 10kN pneumatic grips on a 10kN load cell. The pull rate was 5 mm/min. Smooth jaw faced grips were used for the flexible specimens, and serrated jaw faced grips were used for the rigid specimens. Gauge length, width, and thickness of each sample were recorded in millimeters, and every 0.1 second the extension (mm), tensile stress (MPa), load (N), and tensile strain (mm/mm) were recorded.

2.2 *Results and Discussion*

Ultimate tensile stress values are reported by orientation in Figure 3. Each of the materials corresponds to the listing in Table 1 from the most rigid (VW+) to the most flexible materials (TB+). The rigid and flexible materials are displayed in separate graphs due to large differences in Y-axis scaling. Error bars indicate sample standard deviations of each data point. Similarly, Figure 4 displays the elastic modulus for each material calculated using linear regression. The elastic region of the stress-strain curve was defined where the linear regression R^2 value of the curve was at least 0.97, with the exception of the TB+ ZX-parts, which had R^2 values of at least 0.90.

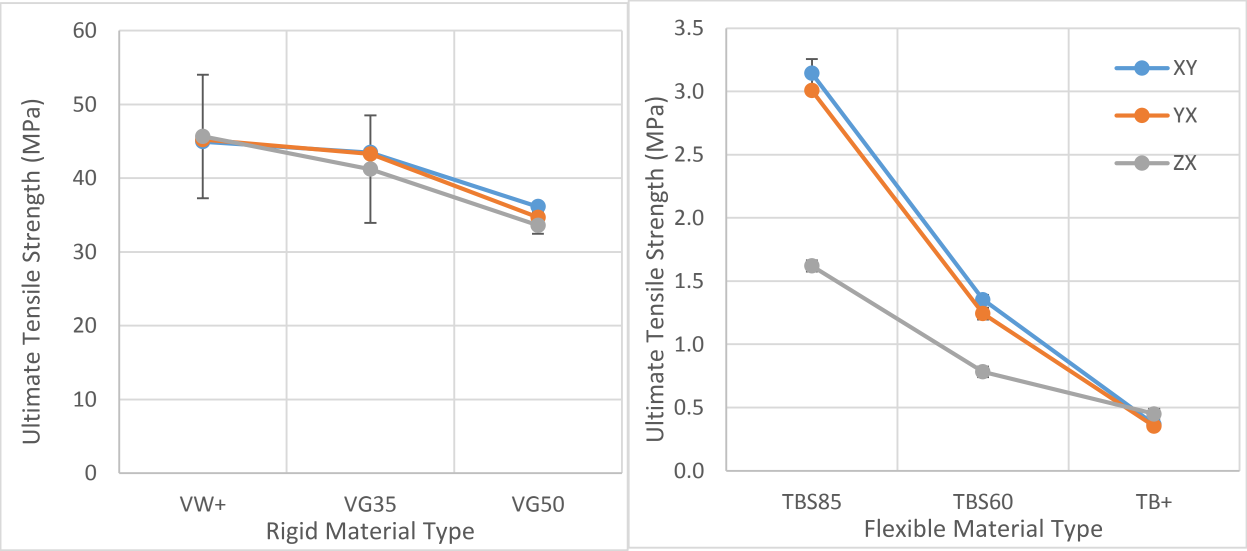


Figure 3. Ultimate tensile stresses for each orientation and material (most rigid to most flexible)

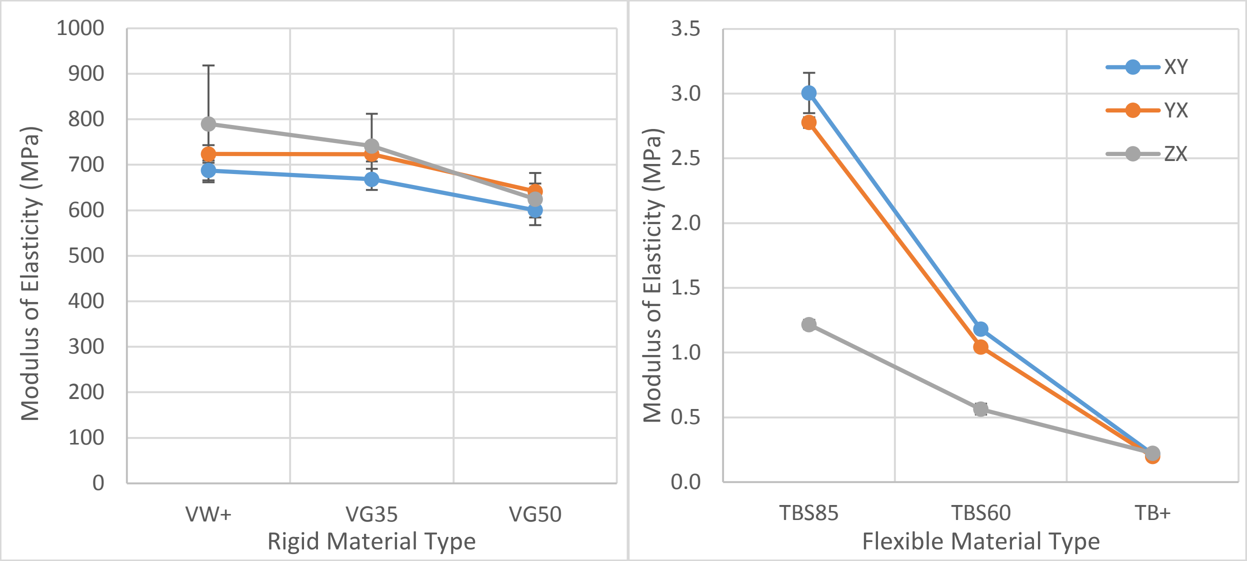


Figure 4. Modulus of elasticity values for each orientation and material (most rigid to most flexible)

The graphs show clear trends of ultimate tensile strength and elastic modulus decreasing with decreased stiffness among all orientations. In general, XY-parts tend to be the strongest while ZX-parts are the weakest (Figure 3). The more rigid materials have relatively similar ultimate stresses, and the VW+ parts indicate nearly isotropic ultimate stress behavior. While modulus of elasticity values for TB+ are similar across orientations, there is clear anisotropy among the other materials. It is possible that this anisotropy manifests itself in part due to the pre-designed dithering patterns used to create the intermediate materials. As the concentration of TB+ in the intermediate materials changes, so may the three-dimensional dithering pattern used to create the material, which may in turn cause the observed increases in anisotropy. While the effects of dithering on the mechanical properties of material jetting parts have been investigated before [19], additional research is needed to confirm this hypothesis.

Although the flexible materials' elastic modulus values parallel the trend for the flexible materials' ultimate stresses, the rigid materials indicate that the ZX-parts have the highest modulus of elasticity with XY-parts having the lowest. Observing the elongation at break of each part in Figure 5 can help justify this inverted trend.

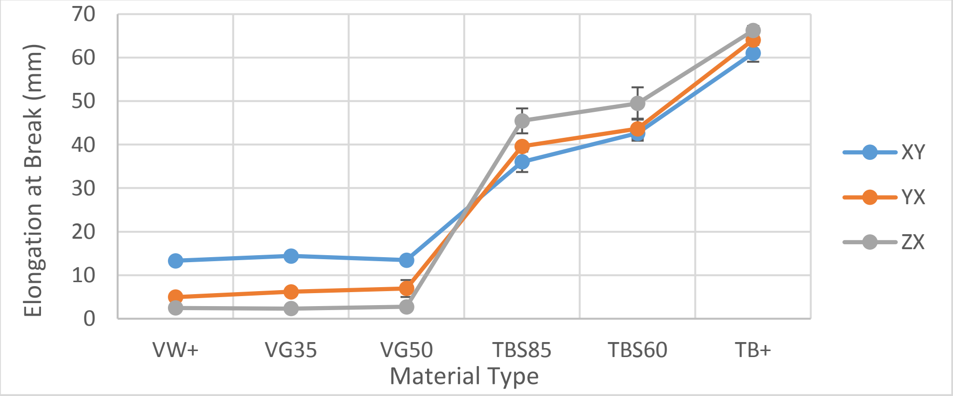


Figure 5. Part elongation at break for each orientation and material (most rigid to most flexible)

Since a more elastic part has a lower modulus of elasticity, it is understandable that the rigid materials have XY-parts elongating the most while having the lowest modulus of elasticity values. Rigid XY-parts tend to also be slightly stronger likely due to how the material was jetted along the direction of tensile strain. In contrast, the rigid ZX-parts elongate the least and are the weakest, potentially because of the tendency for delamination since cross-sectional layers have small surface areas. The rigid ZX-parts have a higher modulus of elasticity verifying that they are less elastic. For the flexible materials, the ZX-parts elongate the most and generally have lower modulus values. The TB+ parts specifically do not vary significantly in ultimate stress nor modulus, which can most likely be attributed to the nature of the rubber-like TB+ material allowing it to exhibit isotropic behavior during fabrication. The horizontal trends in Figure 5 for the rigid materials clearly indicate that small concentrations of TB+ material do not change how much the specimens elongate. On the other hand, the more flexible parts elongate relative to their TB+ material concentration.

T-tests were used to compare the material properties among the various orientations within each individual material. Shown in Table 2 are the p-values, the likelihood of the data to be recreated in a random environment. Any p-value of 0.05 or less has been darkened to signify statistical significance.

Table 2. P-values from t-tests for each material property

	Directions	Ultimate Tensile Stress	Modulus of Elasticity	Elongation at Break
VW+	XY vs YX	0.49	0.10	0.00
	XY vs ZX	0.78	0.24	0.00
	YX vs ZX	0.76	0.43	0.00
VG35	XY vs YX	0.57	0.03	0.00
	XY vs ZX	0.62	0.16	0.00
	YX vs ZX	0.65	0.69	0.00
VG50	XY vs YX	0.03	0.04	0.01
	XY vs ZX	0.02	0.52	0.00
	YX vs ZX	0.22	0.65	0.02
TBS85	XY vs YX	0.11	0.07	0.06
	XY vs ZX	0.00	0.00	0.01
	YX vs ZX	0.00	0.00	0.02
TBS60	XY vs YX	0.03	0.00	0.57
	XY vs ZX	0.00	0.00	0.04
	YX vs ZX	0.00	0.00	0.08
TB+	XY vs YX	0.05	0.01	0.22
	XY vs ZX	0.02	0.23	0.01
	YX vs ZX	0.01	0.00	0.32

The modulus of elasticity and ultimate tensile stress p-values follow similar trends: most of the flexible materials, when compared by orientation, are significantly varying. The TBS85 differences between XY-parts and YX-parts as well as the rigid materials are not statistically significant. Additionally, the p-value of 0.23 for X vs Z in TB+ hints at an isotropic property. The lack of statistical significance in ultimate stress and elastic modulus for the rigid materials points to their isotropic tendency. Elongation data was also statistically analyzed, and all of the rigid materials experience significant differences in extension. For the flexible materials, there is only statistical significance when comparing XY-parts and ZX-parts.

The results from the experiment were compared against the values Stratasys provides in the Digital Materials Data Sheet [16] as shown in Table 3. The elastic modulus values measured in this study are considerably lower than what is reported in the provided data sheet. There is no modulus data presented for the flexible materials. Ultimate tensile stress values match up for the rigid materials, but the flexible materials' measured values were much lower than reported values. The elongation at break data for rigid materials match well, and the flexible materials elongate much more than predicted.

Table 3. Comparisons to the Digital Materials Data Sheet provided by Stratasys [16]

	Ultimate Tensile Stress (MPa)		**Modulus of Elasticity (MPa)**		**Elongation at Break (%)**	
	Predicted	**Actual**	**Predicted**	**Actual**	**Predicted**	**Actual**
VW+	40-60	45.27	1700-2300	733.62	15-25	19
VG35	40-60	42.64	1700-2300	710.88	15-25	22
VG50	35-45	34.8	1400-2000	622.02	20-30	22
TBS85	5-7	2.59	-	2.33	55-65	114
TBS60	2.5-4	1.13	-	0.93	75-85	127
TB+	1.3-1.8	0.39	-	0.21	110-130	180

2.3 *Summary of Key Findings*

The following is a summary of the analysis obtained from this section:

- Parts oriented with the longest direction along the X-axis tend to be the strongest for all material types. Parts oriented with the longest direction along the Z-axis tend to be the weakest.
- For rigid materials, parts oriented along the X-axis have the lowest moduli of elasticity and have the highest elongations at break. Flexible parts in the same direction have the highest moduli of elasticity and the lowest elongations.
- While the variations in flexibility in the rigid materials do not affect their elongations at break, the flexible materials elongate more with increased TB+ concentration for all orientations.
- Although there is a trend of statistical significance for modulus of elasticity and ultimate stress values for most flexible materials, results are inconclusive for rigid materials. For elongations, while all materials exhibit statistical significance between XY- and ZX-parts, only rigid materials have all directions significantly different.

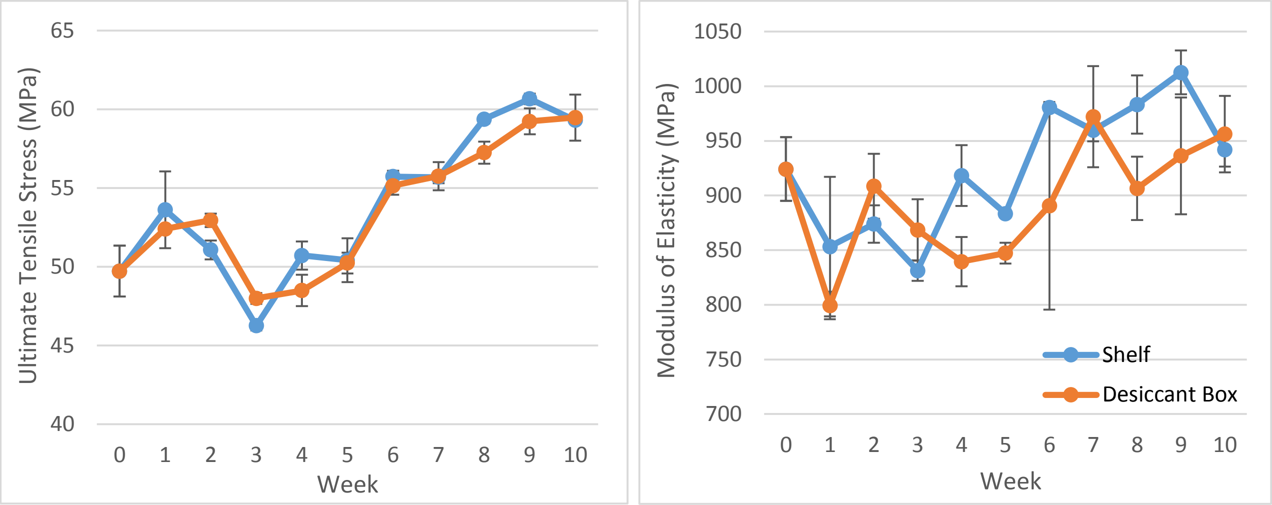
3. EFFECT OF AGING

3.1 *Experimental Methods*

Knowing the effect of time on the material properties of end-use parts is critical when considering the expectation of prolonged part quality. To explore the effect of time on degradation of cured photopolymer, identical part trays were fabricated in the XY-orientation, and parts were tested weekly over ten weeks. Each tray had four VW+ specimens that underwent automatic placement and had matte finish. Two specimens were placed on a shelf with exposure to frequent fluorescent light, and the other two parts were placed in a desiccant box with no light exposure. For each week, two specimens from each location were tested. Tensile testing parameters are identical to those outlined in Section 2, and likewise, humidity and temperature were relatively consistent. Temperatures and relative humidity of both the surroundings and desiccant box were approximately 72˚F and 27% respectively. The experimentation in the following section is intended to explore variability in the mechanical properties of VW+ as it ages to understand how the material jetting process affects part quality.

3.2 *Results and Discussion*

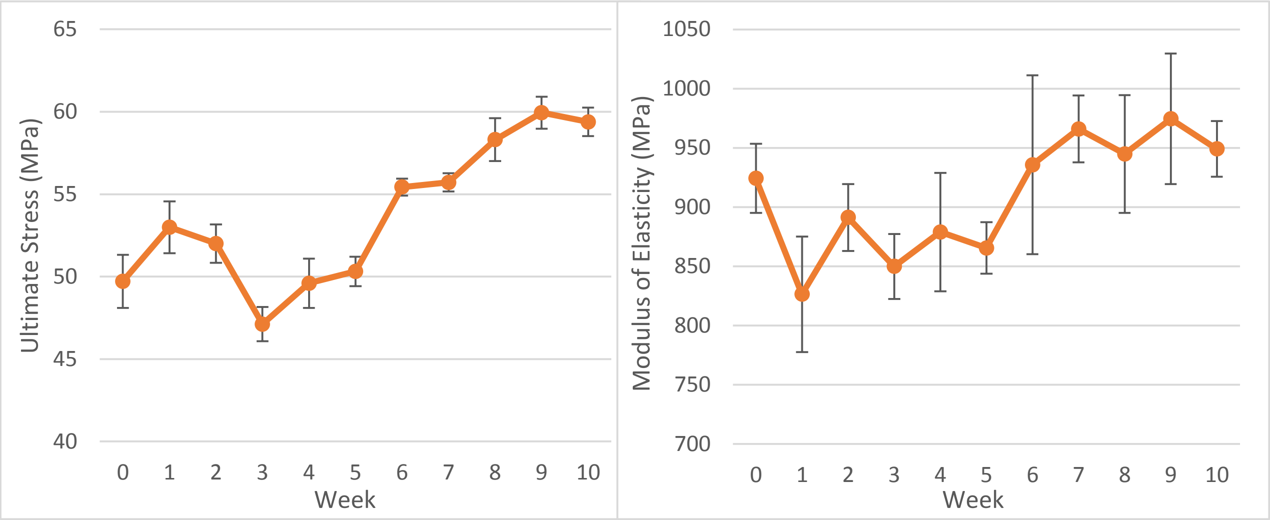
The trends in ultimate stress and modulus of elasticity for each storage location are shown in Figure 6. “Week 0” parts were tested immediately after being printed and are considered the control specimens, and all four samples were averaged together for analysis.



(a) (b)

Figure 6. (a) Ultimate stress and (b) modulus of elasticity values for VW+ over 10 weeks

The ultimate stress values depict a similar trend between the shelf and desiccant box parts. While there is a decrease in strength at the third week, the general trend increases in ultimate stress. It is noticed in Figure 6b that, while slightly increasing over time, the modulus of elasticity of both groups of specimens were fairly consistent over time though the elastic modulus of the desiccant box parts seems to remain slightly lower than that of the shelf parts. To quantify the difference between results of the shelf specimens versus the desiccant-box specimens, a t-test was conducted with results displayed in Table 4. With p-values of 0.05 or less indicating statistical significance, clearly, there was not a significant change in material properties between lighting conditions even though the shelf parts had potential for extra UV exposure from everyday lighting. Since the placement proved irrelevant, the data from Figure 6 was averaged together and replotted in Figure 7. Table 5 shows computed p-values comparing for significance of each week against the control. While the sporadic significant p-values are inconclusive, the ultimate tensile stress is significantly higher starting from the sixth week.



(a) (b)

Figure 7. (a) Ultimate stress and (b) modulus of elasticity values for VW+ over 10 weeks

Table 4. T-test comparing shelf to desiccant box parts

Week	Ultimate Tensile Stress	Modulus of Elasticity
1	0.56	0.36
2	0.07	0.29
3	0.03	0.22
4	0.14	0.09
5	0.89	0.04
6	0.35	0.31
7	0.93	0.75
8	0.06	0.11
9	0.15	0.20
10	0.89	0.65

Table 5. T-test comparing each week to the control week

Week	Ultimate Tensile Stress	Modulus of Elasticity	Elongation at Break
0 vs 1	0.03	0.01	0.34
0 vs 2	0.06	0.15	0.08
0 vs 3	0.04	0.01	0.03
0 vs 4	0.92	0.17	0.06
0 vs 5	0.54	0.02	0.01
0 vs 6	0.00	0.79	0.00
0 vs 7	0.00	0.09	0.01
0 vs 8	0.00	0.50	0.00
0 vs 9	0.00	0.16	0.00
0 vs 10	0.00	0.23	0.00

Elongation at break results are presented in Figure 8 with p-values shown in Table 5. A pronounced downward trend, which is statistically significant after three weeks, points to parts becoming less elastic over time. The slight increase in modulus of elasticity values verify this trend. And just like in Section 2, these trends correspond to higher ultimate stresses. This indicates that as the material sits over time, it may be hardening, which makes it stronger but more brittle.

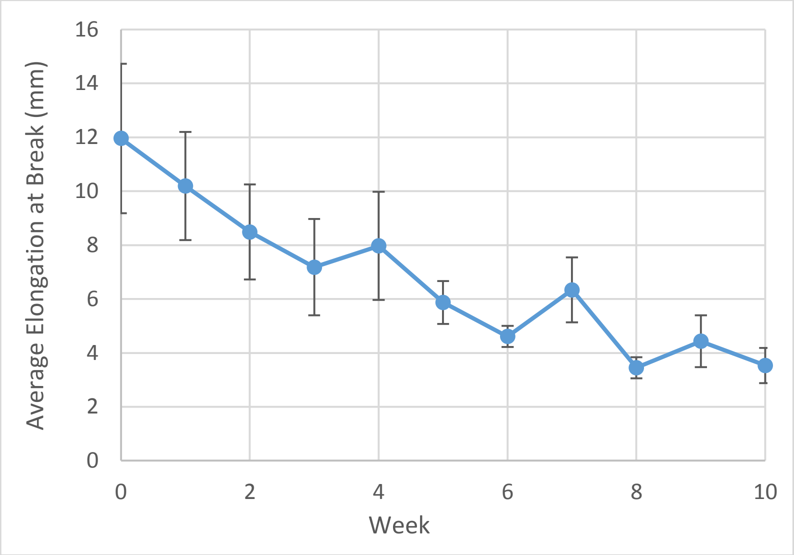


Figure 8. Part elongation at break for VW+ over 10 weeks

3.3 *Summary of Key Findings*

By testing the mechanical properties of VW+ over 10 weeks, the authors are able to conclude:

- The material properties evaluated in this study for VW+ specimens are not significantly affected by different lighting conditions.
- Ultimate tensile stress of VW+ parts increases as parts age. Results are statistically significant after five weeks.
- Modulus of elasticity values were not shown to change at a statistically significant level.
- Elongation at break shows a significant decreasing trend over time.

4. CLOSURE

In order for the material jetting process to make effective end-use parts, there must first be an understanding of how the process affects part quality. The goal of this study was to identify variations in PolyJet digital materials by looking at effects of part orientation and aging. This paper has explored three key mechanical properties (ultimate tensile stress, modulus of elasticity, and elongation at break) of several materials made from two common material jetting photopolymers: polypropylene-like VeroWhitePlus (VW+) and elastomer-like TangoBlackPlus (TB+). Looking at orientation, XY-parts of all materials tended to be the strongest. While rigid XY-parts experienced lowest modulus of elasticity and highest elongations at break, the flexible XY-parts experienced an opposite trend. The investigation into orientation provides the first known research into mechanical behavior of photopolymers containing different concentrations of TB+ material. Regarding aging effects, ultimate tensile stress of VW+ was shown to increase with time, and elongation at break clearly decreased. The material properties of VW+ were not altered by lighting conditions. These findings are the first aging effects studied for the material jetting process.

The findings from this paper present multiple opportunities for future research. To more clearly assess material performance with future studies, tolerances of the parts should be monitored. Most likely to compensate for the elastomer-like material, the TB+ parts were consistently printed smaller than all of the other parts. Analyzing the extent of this build trend was not in the scope of this paper. During tensile testing, it was common to see parts fail at the neck region. Moore and Williams, who studied fatigue life of VW+ and TB+, ran into this same issue with the TB+ parts [20]. Tensile specimens are specifically designed with the smallest cross-sectional area along the gauge length to promote failure in this region; however, because the AM process approximates curves with linear segments, the neck region has frequently become the area for failure. While the effects of this have not been thoroughly examined, a tensile specimen design that performs more consistently with elastomer-like materials should be considered. Future work will also aim to expand the study of aging effects in the material jetting process to multiple materials. As end-use parts vary in their material requirements, an understanding of the aging of TB+ and gradient materials that were studied with orientation in this paper could prove beneficial when making material decisions. Finally, quantifying the relationship between UV-exposure and material properties will be explored in upcoming studies. The scattering nature of light poses the risk for overcuring a part when adjacent layers are scanned. A look into how UV-exposure affects mechanical properties could help evaluate the impact of additional UV-light on part quality. Overall, further investigations into the mechanical properties of AM photopolymers are necessary to continue to improve understanding of the material behaviors so that informed material selections can be made.

5. REFERENCES

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