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Effect of Process Parameters and Shot Peening on Mechanical Behavior of ABS Parts Manufactured by Fused Filament Fabrication (FFF)

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Abstract

The goal of this research was to understand how shot peening affected the tensile strength and elongation of ABS polymer parts between three process parameters: layer height, infill angle, and outer shell quantity. Experiments were conducted using a Hyrel 30M fused filament fabrication (FFF) printer to produce ASTM 638D-IV samples. This is an important area of research because 3D printed polymers have typically been limited to prototyping applications due to low strengths and stiffness. Traditional means of improving a polymer's mechanical properties are changing the structural or chemical makeup. However, shot peening, a surface treatment commonly used to improve mechanical properties of metals, was hypothesized to have a statistically significant effect on the tensile strength and elongation of polymer parts. Results showed that shot peening had a significant effect on decreasing the tensile strength. Although not statistically significant, samples did show an increase in elongation after shot peening.

Keywords: fused filament fabrication, shot peening, ABS, strength, elongation

1. Introduction

Three-dimensional printing is a manufacturing practice that is reshaping industries and producing new opportunities. Polymer printing is a widely studied area in additive manufacturing as it has vast capabilities and is an affordable manufacturing method for custom parts. However, depending on 3D printer quality, mechanical properties vary widely. As desktop printers become more commonplace with hobbyist, small business owners, and K-12 education, the need to print low cost, high quality components quickly and cheaply becomes challenging. There are several methods to improve the mechanical properties of polymer printed parts. The first approach to achieving higher quality parts is optimizing print process parameters. Another option is post-processing that uses chemical, physical, or thermal mechanism to refine mechanical properties. A lesser explored option is the use of surface treatments, such as shot peening, to improve the surface mechanical properties of polymer parts. The use of surface treatments to improve part quality on low-cost printers may be an effective approach to achieve similar results seen by high-end 3D printers.

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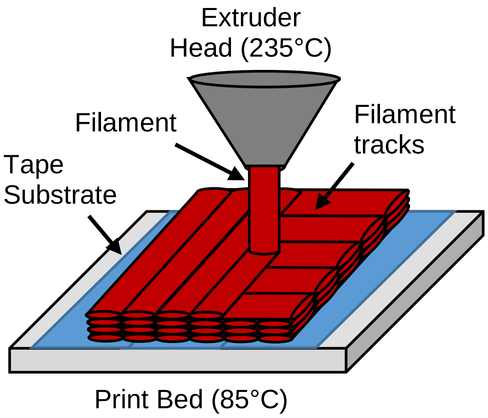
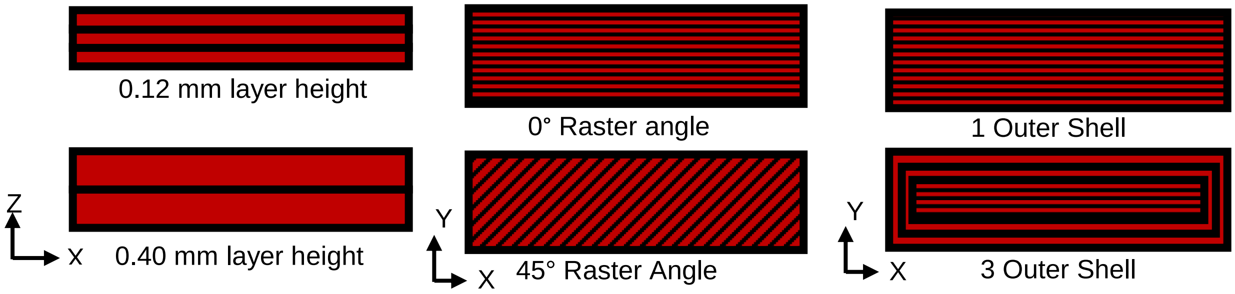


Fig. 1 Fused Filament Fabrication (FFF).

Polymer printing has copious avenues of exploration to understanding the relationship between process parameters and part quality. A common printing process is fused filament fabrication (FFF); see **Fig. 1**. FFF has numerous process parameters leaving voids in the knowledge about their effects on part quality. The FFF process consists of a printer head extruding material (usually heated) onto a build platform producing a 2-dimensional design. This design comes from a 3D model that is sliced into layers and collectively results in a 3D part. FFF allows for nearly any design of a part without additional tooling. Entry-level printers often produce parts with inferior mechanical properties to those produced by traditional processes, such as injection molding. The strength of FFF polymer parts is dependent on parameters such as:

- 2D design layer thickness, **Fig. 2(a)**
- Polymer track orientation, thickness, and spacing, **Fig. 2(b)**
- No. of outer shells encompassing the inner material, **Fig. 2(c)**
- Printing speed (production time)
- Hardware temperatures (nozzle and printing bed).



(a) (b) (c)

Fig. 2 Representation of FFF process parameters: (a) layer height, (b) raster angle (infill angle), and (c) outer shell.

The parameters listed above, in addition to others, allow opportunities to tune the printing process to obtain specific mechanical properties. For example, it was shown that increasing the number of outer shells in a part increases the tensile strength, but reduces elongation characteristics [1-4]. Also, data has shown that smaller layer heights resulted in the highest tensile strength due to an increased cross sectional area according to Garg and Bhattacharya [5]. However, the next strongest sample had the largest layer height tested and was attributed to a reduction in air pockets where cracks would initiate [5, 6]. Raster angle also has variability in research results. Some sources printed consistent raster angles throughout, while others alternated directions between layers. Most sources agreed [5-7] that a 0° raster angle (parallel to loading) resulted in the best tensile strength when maintained throughout the part. Additional research revealed that when alternating between build layers, a 0°/90° setup was better compared to only 0°, 45°, or 90°

angles [8, 9]. Even still, others have found that 60° and higher raster angles resulted in a stronger tensile strength [10, 11]. This indicates inconsistent results on raster angle's effect on strength.

Post processing methods are another way to manipulate material properties like tensile strength and elongation. Many methods exist, but shot peening is a quick, low cost, and straight-forward option. Shot peening uses small spheres (media) at a high velocity to plasticize a surface, thus inducing a beneficial compressive residual stress, (**Fig. 3**). This stress increases crack resistance in the outer surface of the material and alters other mechanical properties [12]. Shot peening parameters can be adjusted depending on the user's goal. First, the media size and material can be changed depending on the amount of surface area to cover and what type of surface is present. Peening speed, which is dictated by pressure and nozzle diameter, can change to increase the depth of penetration [13].

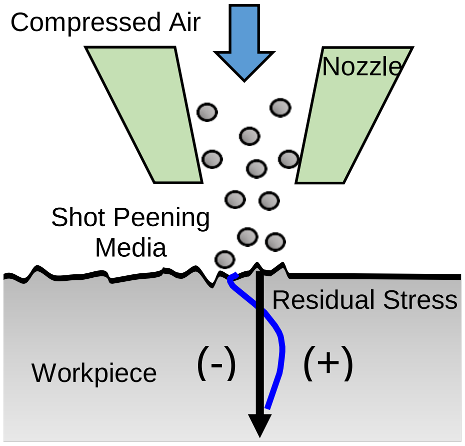


Fig. 3 Shot peening process.

Both FFF and shot peening are useful processes that allow many parameters to be adjusted. There was no reported literature on the use of shot peening on polymers, most likely due to the limited structural use of polymers. All reported shot peening literature related to additive manufacturing has been conducted on metal alloys. The purpose of this research was to investigate the strength and elongation of an ABS polymer printed on an entry-level machine by adjusting process parameters and incorporating shot peening. Shot peening was implemented due to its effectiveness of changing mechanical properties and efficient cost of operation. Results from this experiment will determine the feasibility to use shot peening as a supplemental processing step to improve mechanical properties.

2. Experimental Setup

2.1 Fused Filament Fabrication

Two different types of samples were printed using ABS filament with a 1.75 mm diameter. First, an ASTM 638D Type IV "dog bone" part shown in **Fig. 4(a)** was used for the purpose of tensile and fracture strength testing in addition to elongation measurements. Second, a flat pseudo-Almen strip sample as shown in **Fig. 4(b)** was dimensionally identical to an A-2 Almen strip and used for preliminary work to determine shot peening process parameters.

Fig. 4 Sample geometry: (a) ASTM 638D Type IV and (b) pseudo-Almen strips.

For both samples, three print process parameters were changed as part of a central composite design to maximize efficiency. These parameters had low, center, and high values which were within the acceptable range of each parameter's capability. **Table 1** shows the levels for layer height, raster angle, and number of outer shells used in this experiment. These values produced nine total "printing recipes" which consisted of (a) eight recipes with every combination of the low and high variables and (b) one recipe exclusively with the center points of each variable. Each of the eight recipes of low/high had 3 repetitions (**n = 3**), while the center point had 9 repetitions (**n = 9**). In addition to changing the main process parameters, the material flow rate factor (dependent process parameter) was adjusted to accurately achieve the desired layer heights, as seen in **Fig. 5**. All other printing parameters can be referenced in **Table 3A** in the Appendix.

Table 1 Levels of Layer height, No. of Outer Shells, and Raster Angles

Variable	Levels (Low, center, high)
Layer Height	0.12 mm, 0.26 mm, 0.40 mm
No. of outer Shells (X-Y plane)	2,3,4
Raster Angle (from loading)	9°,23°,36°

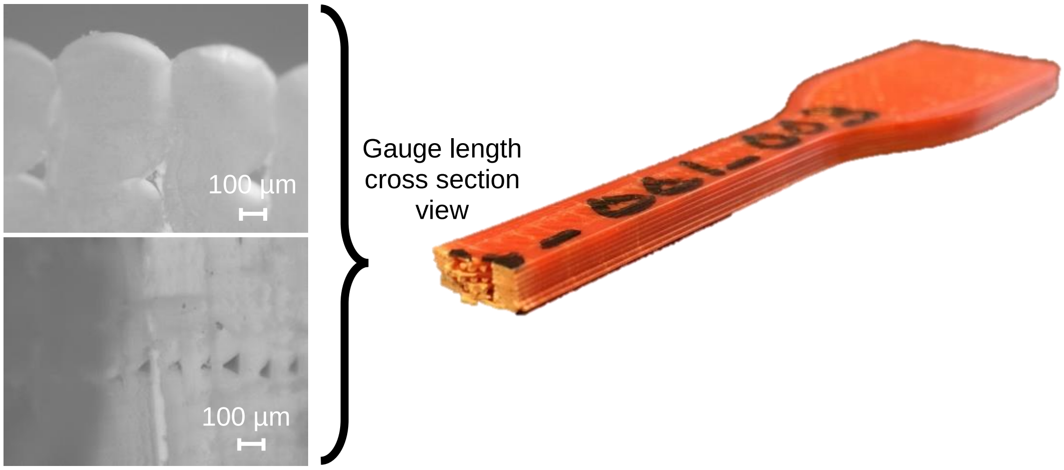


Fig. 5 Microscopic image of layer height: (a) low layer height (0.12 mm) and (b) high layer height (0.40 mm).

All parts were printed on a Hyrel 30M fused filament fabrication (FFF) machine as seen in **Fig. 6**. A specific procedure was executed during the production of parts, which included part placement, printing, and removal. Only three parts were printed at one time, as shown in **Fig. 7**, in order to be efficient while reducing random thermal gradients. Manufacturing of the parts started when the minimum print bed and nozzle temperatures were met (**Table 3A** in the appendix). Prior to all print jobs, the machine's z-calibration, which is the distance between the bed and nozzle, was either validated or recalibrated to be at the manufacturer's recommended distance (approximately 1 mm). Finally, parts were removed using a razor blade to gently "pop" the longer edge of the part below the painters' tape substrate as shown in **Fig. 7**. The tape allowed for better adhesion to the print bed and a buffer for removing parts to avoid damage with the razor blade.

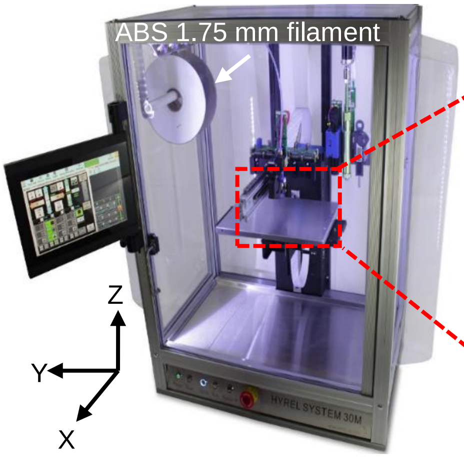


Fig. 6 Hyrel 30M fused deposition modeling (FDM) machine.

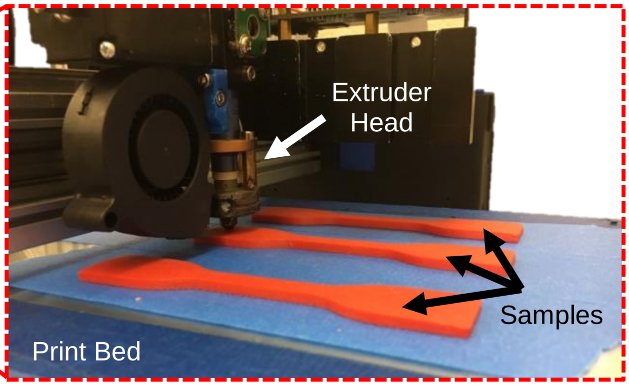


Fig. 7 FFF build platform.

2.2 Shot Peening

Shot peening severely bent the samples due to imbedded residual stresses. Here, the pseudo-Almen strip samples were shot peened to exploit their ability to easily measure the curvature resulting after peening. Pseudo refers to the fact that Almen strips pertain strictly to metals to determine saturation. The change in curvature, or deflection, was measured using pictures taken immediately after peening of the sample parallel to the peened surface. The deflection of each strip was measured in seven locations equally spaced from the center (**Fig. 8**). With this procedure, one combination of variables (or recipe) was peened with 10, 20, 30, 40, or 50 passes at a rate of 10 passes per minute (3 samples for each recipes). The deflected strips were used to develop the saturation curve, which was later validated with all remaining recipes by comparing their deflections for consistency. At 20 passes, all recipes had negligible differences in their deflection indicating a saturation point where significant further deflection was minimal. **Table 2** gives the parameters used for shot peening the dog bone samples. Shot peening was done using a Westward blast cabinet equipment with a pressure regulator. To produce consistent results, the jig in **Fig. 9** was used to secure the sample.

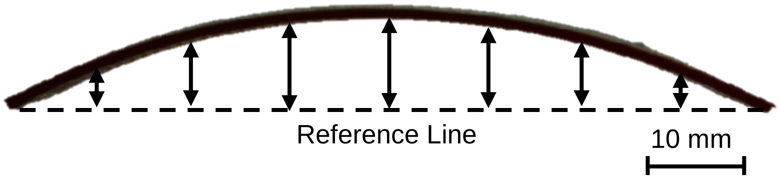


Fig. 8 Pseduo-Almen strip deflection after shot peening.

Table 2 Shot Peening Process Parameters

Parameter	Value
Media Type	Glass
Media Size	0.4-0.6 mm
Air Pressure	0.55 MPa
Nozzle Diameter	4.76 mm
Contact Distance	100 mm
No. of passes	20
Application Rate	10 passes/minute

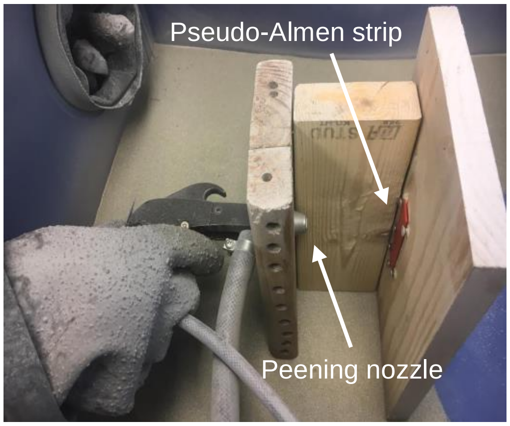


Fig. 9 Shot peening fixture.

2.3 Tensile Testing

Tensile testing was performed on a MTS 810 equipped with a 25-kN capacity load-cell and an extensometer measuring a distance of 25 mm as seen in **Fig. 10**. The non-gauge length ends of the samples were securely fastened in the upper and lower grips. The strain rate was 0.01 mm/min and the data sampling rate was 0.10 seconds. Due to a testing failure, only 8 were used in the results. Calipers were used prior to fracturing to measure the actual sample gauge width and height. With the cross-sectional area, stress for each sample was calculated.

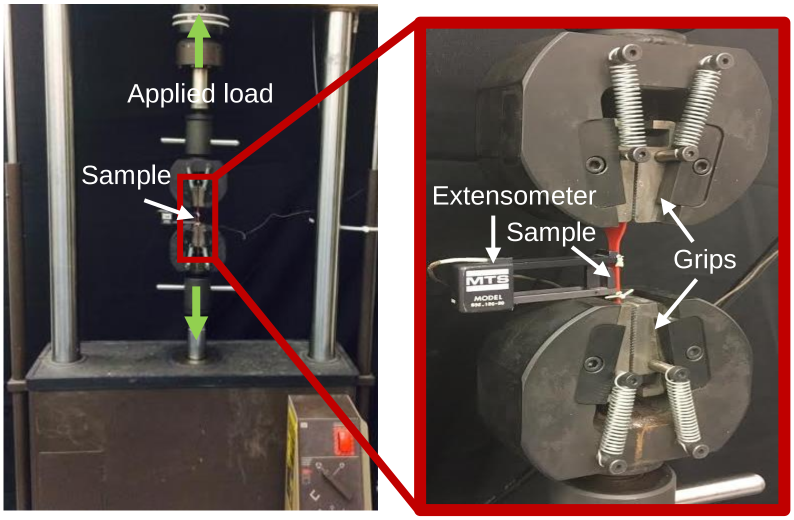


Fig. 10 MTS 810 tensile testing machine setup.

3. Results and Discussion

3.1 Elongation

3.1.1 Scatter Plot Results

Layer height and shot peening were found to influence elongation (**Fig. 11(a)**). The peening process increased the 0.12 mm and 0.40 mm layer heights' maximum elongation from 2.34 mm to 2.50 mm and 2.35 mm to 2.42 mm, respectively. However, shot peening decreased the elongation effects for the 0.26 mm layer height from 2.13 mm to 2.10 mm. The smaller layer height accepted the shot peening process as beneficial because the inside material was well packed (lots of small voids between raster tracks). In contrast, the larger layer height beneficially accepted the surface treatments because its inner material was also well packed, but due to fewer large air voids between raster tracks. The center point of the central composite design hits a critical point where numerous sizeable air voids occur between raster tracks and dilute the effects of shot peening. This same logic of air voids between layers is the reason why the 0.12 mm and 0.40 mm layer heights performed similarly. In contrast, the 0.26 mm layer height resulted in the lowest elongation because its cross sectional area was the least due to a poor balance of thick raster tracks and voids between rasters.

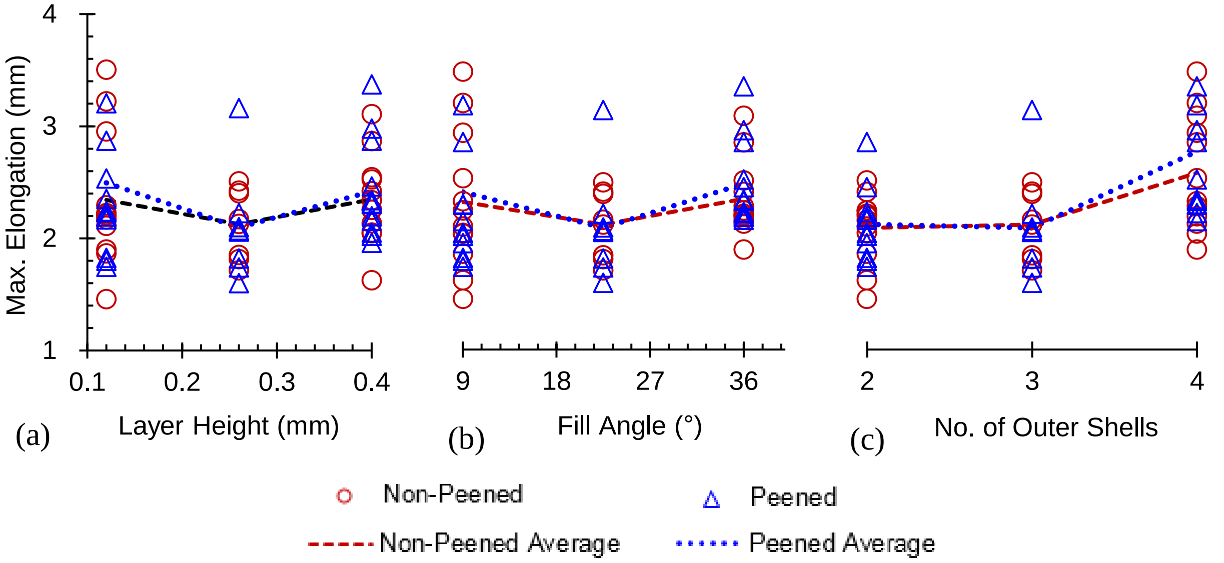


Fig. 11 Effect of print parameters and shot peening on elongation: (a) layer height, (b) fill angle, and (c) No. of outer shells.

Raster angle's most significant contribution with the addition of shot peening was increasing the 9° and 36° maximum measured elongation. Both raster angles (9° and 36°) experienced increased elongation effects with shot peening from 2.33 mm to 2.42 mm and 2.36 mm to 2.49 mm, respectively. At the center point of 22.5°, shot peening decreased the elongation of samples from 2.13 mm to 2.10 mm. When looking at the scatter plot in **Fig. 11(b)**, the range of measured values for the 9° infill angle is vast, but has a concentrated cluster around the 2 mm mark. With this dense area of data, and a handful of outliers that measured 3.5 mm or greater elongation, these outliers pulled the average of the 9° samples above that of the 22.5° raster angle samples. If the data had not followed this path, it would have shown an increased infill angle (up to 45°) would increase elongation, thus agreeing with prior literature.

Samples with two and three outer shells had a negligible effect on elongation, *i.e.*, less than a 2% change. When printing at these conditions, on average, samples differed in elongation trends with values changing from 2.10 mm to 2.13 mm and 2.13 mm to 2.10 mm with shot peening, respectively. With 4 outer shells, shot peening had a noticeable effect with increased elongation from 2.59 mm to 2.79 mm after peening. This 10% increase in elongation is believed to occur because at 4 outer shells, enough peripheral material was present for shot peening to beneficially manipulate the mechanical properties of this section and reduce crack initiation and growth. **Fig. 11(c)** shows that more outer shells increased the elongation capabilities for the same reason previously stated; *i.e.*, more outer material slows crack propagation.

3.1.2 Main Effects and Interactions

An effects plot that includes interaction terms for shot peened and non-shot peened ABS tensile samples is shown in **Fig. 12** to convey what parameters were most influential. Shot peening increased the displacement for the majority of printed parts. This figure shows adjusting the quantity of outer shells alone had the greatest effect on elongation. Adjusting the layer height alone had the least significant effect on elongation. For most samples, adjusting any two parameters or all three at once had a greater influence over elongation than individual parameters. Finally, these results were consistent with peened and non-peened samples except for No. of shells and infill angle, which was the third most influential factor over all three parameters when not being peened.

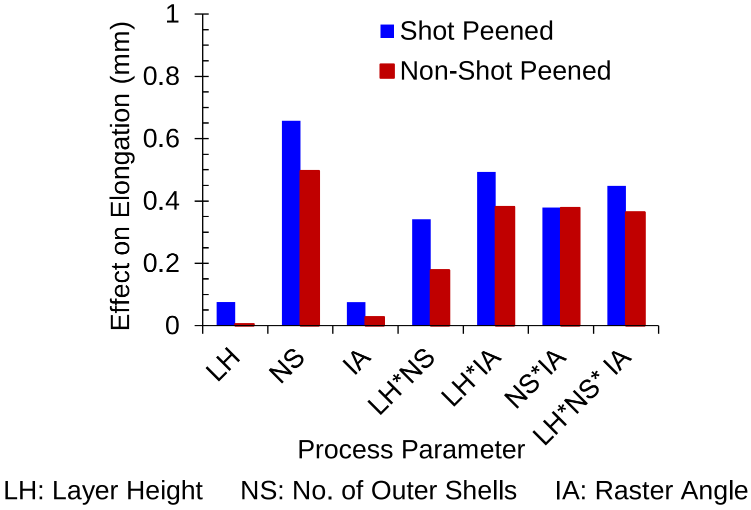


Fig. 12 Main and interaction effects of process parameters and shot peening on elongation.

Due to the small amount of change in the elongation of all samples, an ANOVA test was conducted to determine the significance of each of the three process parameters, plus the peening condition. The test was conducted using a 95% confidence level. **Table 3** lists the results of this ANOVA test for all four process parameters. Infill angle was the only parameter which had elongation results that showed significance. The other two printing parameters and the peening parameter were not significant. That is, the *p*-values were greater than 0.05.

Table 3 ANOVA test with 95% confidence level for displacement

Variable	P-Value
Layer Height	0.811
Infill Angle	0.000
No. Outer Shells	0.729
Shot-Peening	0.452

3.2 Tensile and Fracture Strengths

3.2.1 Scatter Plot Results

Tensile and fracture strength results for various layer heights had similar trends regarding printing process parameters and shot peening effects. After shot peening, tensile strength changed from 26 MPa to 24 MPa and 22 MPa to 23 MPa for the 0.12 mm and 0.26 mm layer heights, respectively (**Fig. 13**). With a layer height of 0.40 mm, shot peening had no effect as non-peened and peened samples averaged 24 MPa of tensile strength. Ultimate fracture strengths for 0.12 mm and 0.26 mm samples resulted in changes of 24 MPa to 21 MPa and 20 MPa to 21 MPa after shot peening. Similar to ultimate tensile strengths, the fracture strength did not change, on average, after shot peening as both non-peened and peened samples resulted has a fracture strength of 22 MPa. Consistently, the 0.26 mm layer height resulted in the lowest tensile and fracture strengths with or without peening. The maximum tensile and fracture strengths for non-peened samples were produced at the 0.12 mm layer height in contrast to peened samples, which were at the 0.40 mm. This is because the smaller layer heights created more surface area within the cross sectional area. But, with shot peening, these thin layer heights were damaged and could not collect residual stress, thus leading to a decline in their respective tensile and fracture strengths.

Outer shell quantity had similar trends for ultimate tensile and fracture strengths when shot peening was introduced (**Fig. 14**). For two outer shells, a decrease in tensile strength from 21 MPa to 20 MPa was observed for samples which were peened. For fracture strength, no change occurred, on average, as both non-peened and peened samples has a fracture strength of 19 MPa. At three outer shells, shot peening increased both the tensile and fracture stresses by about 5%. Non-peened samples exhibited 22 MPa of tensile strength, and peening them increased that to 23 MPa. The opposite occurred with four outer shells. Non-peened samples exhibited a tensile strength of 29 MPa compared to peened samples with a tensile strength of 28 MPa. Fracture strength of non-peened samples measured 26 MPa while peened samples were 25 MPa. Therefore, at four outer shells, about a 3.5% decrease in both tensile and fracture strengths resulted. The quantity of outer shells as a printing process had a more significant effect on ultimate tensile and fracture strengths as both increased by approximately 35% for non-peened and peened samples.

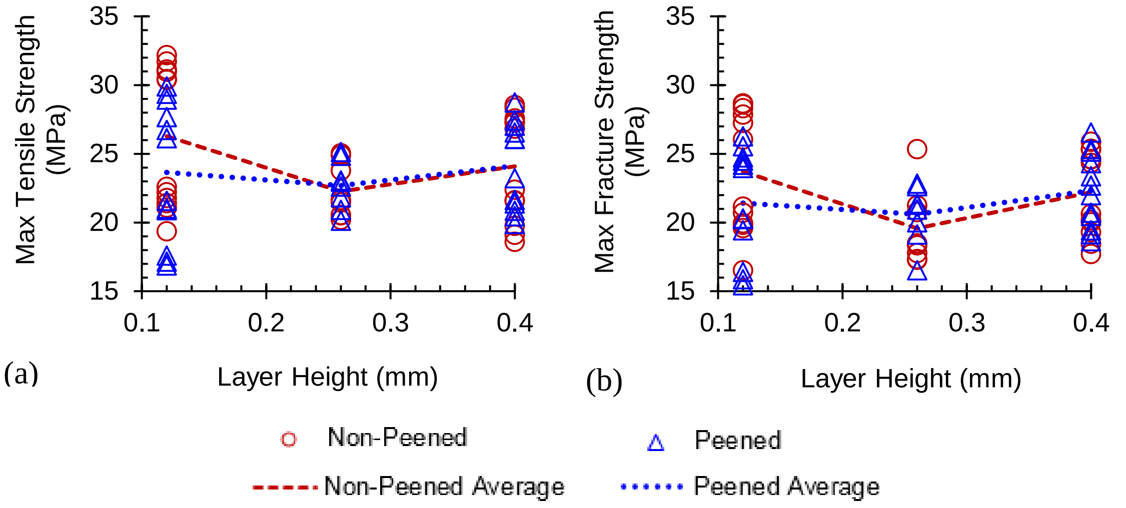


Fig. 13 Effect of layer height and shot peening on (a) tensile strength and (b) fracture strength.

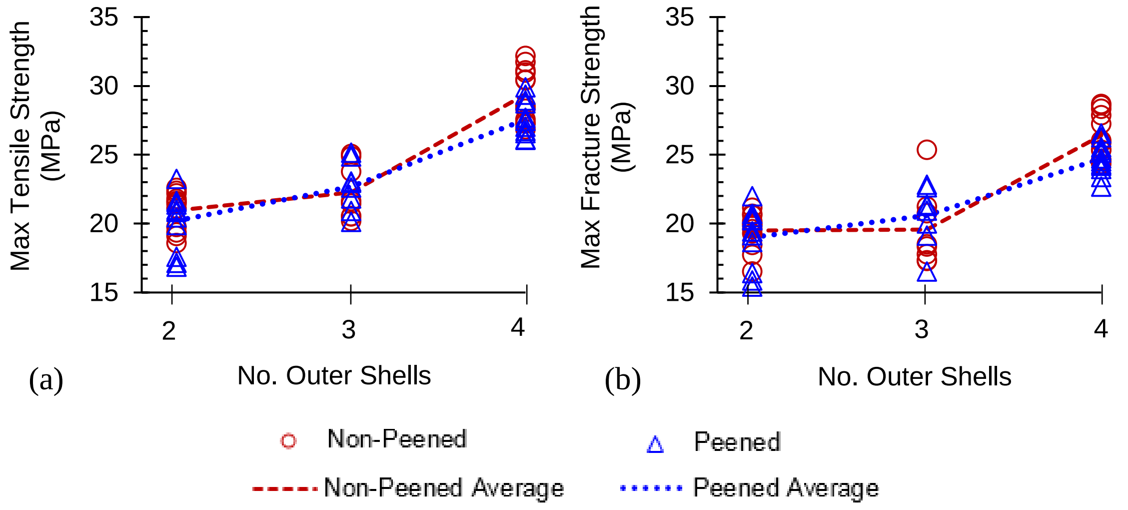


Fig. 14 Effect of outer shells and shot peening on (a) tensile strength and (b) fracture strength.

Raster angle exhibited consistent trends between printing parameters and peened/non-peened samples (**Fig. 15**). Ultimate tensile strength changed for both the 9° and 22.5° raster angles going from 25 MPa to 23 MPa and 22 MPa to 23 MPa, respectively. The fracture strength also changed in a similar manner, 23 MPa to 21 MPa, and 20 MPa to 21 MPa for 9° and 22.5°, respectively. For the 36° samples, no change occurred as the tensile strength was 25 MPa and the fracture strength was 23 MPa. This trend was consistent with literature; that is, the 45° alternating raster angle exhibits the greatest tensile and fracture strength as compared to 0°, 90°, or 0°/90° patterns.

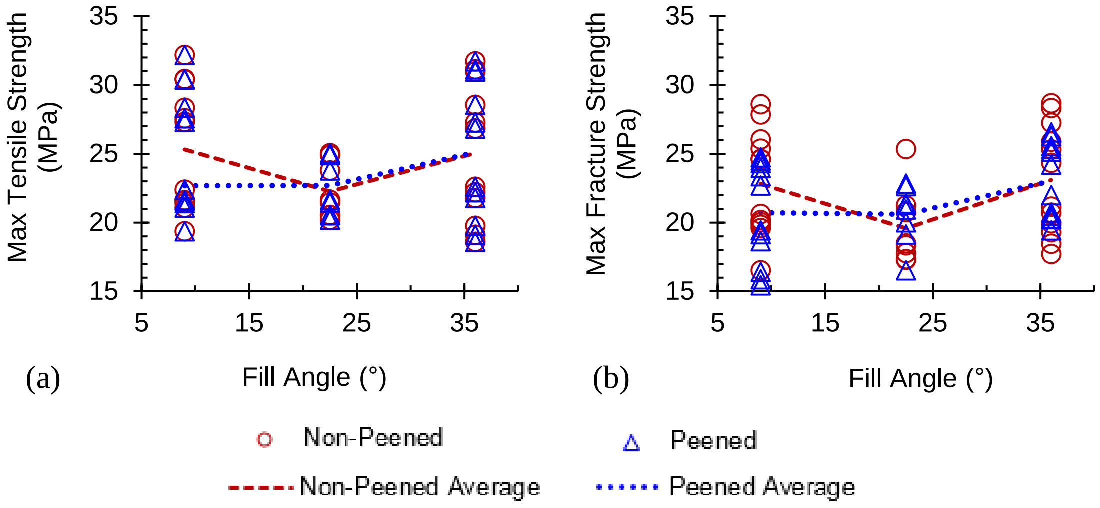


Fig. 15 Effect of fill angle and shot peening on (a) tensile strength and (b) fracture strength.

3.2.2 Main Effects and Interactions

Fig. 16 plots the effectiveness of each individual parameter and the interaction terms to show which are most sensitive to changing the tensile strength. For both non-peened and peened samples, No. of outer shells had the greatest effect on manipulating the tensile strength of a printed part. This was because outer shell quantity dictates how much material through which a crack must propagate. Without peening, layer height was second for the most influential parameter regarding tensile strength. However, it was nearly negligible after peening. With and without peening, adjusting both infill angle and outer shell quantity had the least effect on tensile strength except for shot peened samples where all three parameters were changed.

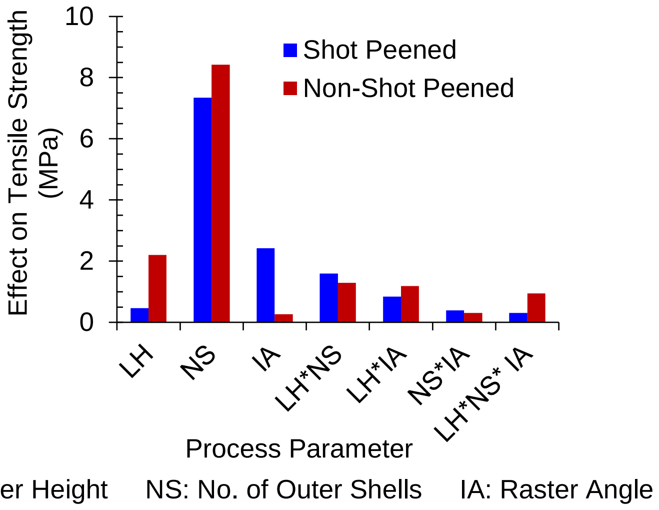


Fig. 16 Main and interaction effects of process parameters and shot peening on tensile strength.

To build upon the results of this section, an ANOVA test was conducted on the tensile strength data. This 95% confidence level test was conducted because similarly to the elongation results, the changes in tensile strength between samples was small relative to their values. However, the results of the ANOVA test shown in **Table 4** were significant for almost all fields. Infill angle, number of outer shells, and the shot peening parameters were well within tolerance for being significant for the 95% confidence level. Only the layer height term was not significant, just narrowly being outside the threshold for significance (0.05 in this study).

Table 4 ANOVA test with 95% confidence level for tensile testing

Variable	P-Value
Layer Height	0.071
Infill Angle	0.000
No. Outer Shells	0.013
Shot-Peening	0.008

4. Summary & Conclusions

Several trends were observed by adjusting 3D printing process parameters and applying shot peening as a surface treatment to ABS printed parts on a fused filament fabrication (FFF) system. First, **Fig. 17** shows a generalized stress-strain schematic of observed trends. In nearly every printing recipe (except one), shot peening reduced the ultimate tensile and fracture strengths, which may be attributed to multiple factors. One factor that may have caused reduced strength was improper shot peening practices. Over peening or peening with worn glass beads (sharp, small fractured beads as compared to smooth circular ones) can damage the surface and even produce micro-cracks instead of inducing favorable compressive residual stresses. Another possible explanation was that polymers do not form beneficial residual stress fields as well as metals. The second noticeable trend from this study was that most samples exhibited increased elongation. This trend was more substantial on samples printed with four outer shells. Having more layers on the outer edge led to parts with better elongation characteristics because there was more material for cracks to propagate through. Additionally, this material was able to beneficially absorb some of the shot peening effects and reduce crack propagation.

Another important note from this experiment was that the number of outer shells was the most influential factor in determining ultimate tensile strength and maximum elongation, regardless of whether samples were peened or not. This means that when choosing to adjust layer height, raster angle, or No. of outer shells, changing the outer shell quantity was the most effective. Another trend was that all three processing parameters were more influential in groups then individually when it came to maximum elongation. This was not as observable for ultimate tensile strength, as other printing process combinations were equally as influential and less than outer shell's effectiveness by a factor of three. In addition, ANOVA tests were conducted on all 4 process parameters (printing and peening) which revealed a decrease in tensile strength with significance (95% confidence level), except when adjusting the layer height. In contrast, only the infill angle parameter had significance with regards to the results for elongation.

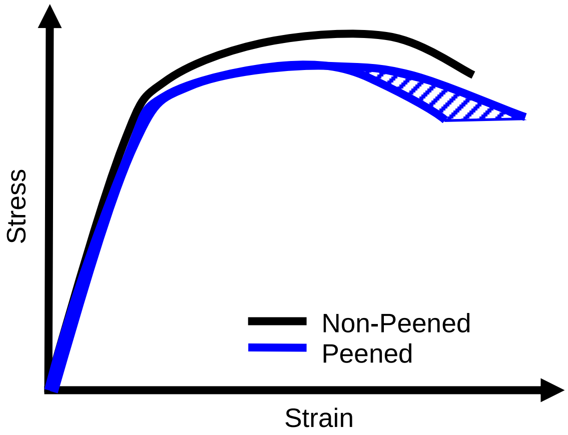


Fig. 17 Representation of stress-strain results for non-peened and shot peened ASTM 638D.

These results show the variability of FFF entry-level printers. Without any surface treatment, it was shown that adjusting process parameters for ABS on this FFF Hyrel 30M printer resulted in tensile strength and elongation trends that contradicted prior research. Additionally, shot peening was shown to have an impact on the mechanical behavior of polymers. Although tensile strength decreased after shot peening, maximum elongation was improved. This shows that shot peening was effective as a supplemental solution to optimizing mechanical properties in a way that was more efficient than using a professional grade printer initially. Both technologies have their place, but this research shows there is multiple ways to achieve a desired result regarding 3D polymer printing and merits further study.

5. Acknowledgements

Undergraduate and graduate students conducted this research as a course project in MECH 498/898: Additive Manufacturing at the University of Nebraska-Lincoln (UNL). The authors would like to acknowledge the support of the Department Chair in Mechanical and Materials Engineering at UNL, Dr. Jeffrey Shield, for enabling Drs. Rao and Sealy to develop a research-based course in additive manufacturing in order to spur more undergraduate involvement in research.

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7. Appendix

Table 3A Hyrel System 30M Printing Parameters

Parameter	Value	Parameter	Value
Solid layer top	0	Infill Extruder	1
Solid layer bottom	0	Solid Infill Extruder	1
Spiral vase	Off	Support material extruder	1
Extra perimeter if needed	On	Support material interface extruder	1
Avoid crossing perimeters	On	Enable	Off
Detect thin walls	On	Temperature variation	-5 Δ°C
Detect bridging perimeters	On	Interface shells	Off
Seam position	Random	Default extrusion width	0.55
External perimeters first	Off	First layer	0.55
Fill density	70%	Perimeters	0.55
Fill pattern	Rectilinear	External perimeters	0.55
Top/bottom fill pattern	Rectilinear	Infill	0.55
Combine infill every ___ layer	1	Solid infill	0.55
Only infill where needed	Off	Top solid infill	0.55
Solid infill every ___ layers	0	Support material	0
Solid infill threshold area	9 mm^2	Infill/Perimeters overlap	15%
Only retract when crossing perimeters	On	Bridge flow ratio	1
Infill before perimeter	Off	XY size compensation	0 mm
Brim width	0 mm	Threads	8
Skirt loops	2	Resolution	0 mm
Distance form object	5 mm	Nozzle temp	235 °C
Skirt height	1	Bed temp	90 °C
Minimum extrusion length	0	Cooling fan	0%
Generate support material	Off	Nozzle diameter	0.5 mm
Overhang threshold	35°	Material diameter	1.75 mm
Enforce support for the first __ layers	0	Material type	Red ABS
Raft layers	0	Z calibrate	0.1 mm
Max volumetric speed	0 mm^3/s	Perimeter extruder	1
Pattern	Pillars		
Pattern spacing	2.5 mm		
Pattern angle	0°		
Interface layers	3		
Interface pattern spacing	0		
Don't support bridges	Off		
Perimeters	30 mm/s		
Small perimeters	30 mm/s		
External perimeters	30 mm/s		
Infill	30 mm/s		
Solid infill	30 mm/s		
Top solid infill	30 mm/s		
Support material	30 mm/s		
Support material interface	100%		
Bridges	30 mm/s		
Gap fill	30 mm/s		
Travel	30 mm/s		
First layer speed	30 mm/s		
Perimeters	0 mm/s^2		
Infill	0 mm/s^2		
Bridges	0 mm/s^2		
First layer	0 mm/s^2		
Default	0 mm/s^2		
Max print speed	30 mm/s		
Contact Z distance	0.2 mm detachable		
Bed substrate	Painters tape		