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Reviewed Paper

Impact of Vapor Polishing on Surface Roughness and Mechanical Properties for 3D Printed ABS

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Abstract

Additive manufacturing (AM) is useful when creating complex geometric models and prototypes. However, a well-known drawback is the fact that parts produced by AM methods typically have lower strength and higher surface roughness than traditionally-formed parts. To compensate for this, the surface finish is commonly improved by mechanical finishing or some type of coating. Another widely used surface treatment for ABS components is vapor polishing. In this process, the part is exposed to a solvent vapor that partially dissolves a surface layer and enables smoothing through surface tension-driven flow; it is known to decrease the surface roughness. However, little work has been reported quantifying the surface roughness change or on the mechanical impacts of this processing method. This work compares the strength, ductility and surface finish of vapor-polished ABS tensile specimens of varying thicknesses (1 mm, 2mm, and 4 mm). Results show that elongation at break is improved, while the modulus of elasticity is reduced in thin specimens. The tensile strength is largely unchanged. The power spectral density for roughness features larger than 20 μm were reduced 10X.

Introduction

Additive manufacturing designates the formal expression for the manufacturing process popularly known as “3D” printing or rapid prototyping. AM processes are best-suited for low volume production runs because no part-specific tooling is required. Many AM processes are based on conventional printing processes such as inkjet and laser printing with stacked layers. The term “3D printing” emphasizes this connection and is commonly applied to the low cost AM processes. Another distinct advantage of AM over traditional manufacturing includes the ability to create highly complex parts of near arbitrary geometry. [1, 2] This advantage essentially allows designers to bypass the “design for manufacturing” step that is crucial to traditional manufacturing methods like casting.

One of the most common AM processes resides in material extrusion technologies. This process works most often with thermoplastic material in either a filament or pellet form. A pinch-roller or screw system feeds the material into a heated extrusion head [3]. The thermoplastic material begins to liquify in the heated extrusion head and then is deposited onto a heated platform through the nozzle. The material flow through the nozzle is controlled by the volume of material fed into the nozzle. The pressure drop between the liquifying chamber in the nozzle and the surrounding atmosphere can produce a time delay between changes in the rate of volume input and flow through the nozzle [4]. A computer generates a numerical code for the coordinates of a “sliced” digital file of a prototype or part and these coordinates become the pathways or “roads” for material deposition of part geometry. Once the extruder head deposits the first layer of material,

the heated platform will descend or the extrusion head will rise one layer height and proceed to deposit the material in a layer by layer fashion. This process again acknowledges the "additive" approach of AM as the extrusion head adds material layer by layer. Extrusion technologies depositing layers in this fashion are often termed Fused Deposition Modeling or "FDM" machines, first produced and developed by Stratasys [5].

The FDM process is the quintessential AM process because it is the process most people think of first when someone mentions "3D printing." However, unlike plastic parts manufactured by traditional methods such as casting or injection molding, parts manufactured by the FDM process suffer certain drawbacks. These drawbacks have stifled their use in many of the applications that would benefit from the free-form fabrication that additive manufacturing has to offer. FDM commonly prints with the material of Acrylonitrile Butadiene Styrene (ABS). These parts are typically rough due to the discrete layers and roads of the deposition. They also warp often and have anisotropic mechanical properties significantly worse than their bulk-manufactured counterparts. [6-10] It is these drawbacks that limit applications of the FDM process. Once these limitations are addressed, the FDM process will find wider range of application.

One approach to improving the surface finish is through post-processing methods. Many parts are mechanically polished or coated to improve the surface. However, another post-processing technique gaining particular interest for ABS is vapor polishing. Vapor polishing acts as a surface treatment to reduce the surface roughness with the potential to maintain dimensional accuracy without significantly eroding part geometry. [11-13] It is also relatively low-labor process compared to mechanical polishing and coating. Vapor polishing introduces a solvent solution with a significant vapor pressure (acetone) that absorbs into to the ABS parts and penetrates the polymer. The solvent dissolves the polymer, and the surface tension forces drive a reduction in the surface roughness in a process similar to viscous sintering. This produces a more even, smooth, and better quality surface finish. In prior work on thermoplastic parts, controlled solvent exposure has shown to improve strength of weld-lines when joining ABS geometries as well [14]. The following experiments show the benefits of using vapor polishing as a post-processing method to improve the mechanical properties, as well as the surface finish, of ABS FDM parts.

Experimental Methods

For mechanical testing purposes, parts were printed according to ASTM Standard D638–10 [15]. The dimensions of the tensile barbell specimens are shown in Figure 1. These barbells were printed on a Stratasys uPrint SE machine in ABS Plus material with various thicknesses of 1, 2, and 4 mm. The parts were printed with the long axis oriented in the z-direction (normal to the print bed) and the ZXY plane – as designated by ASTM F2921 [16]. The z-direction typically has the highest surface roughness and weakest bond strength between deposited layers of FDM fabricated components; therefore, the z-direction was selected as the print orientation. This was done in hopes to reveal the effect of surface roughness and mechanical properties between unpolished and polished samples. Figure 2 below illustrates a sample tensile specimen being printed with included dashed lines as deposition lines where layers bond together. Dissolvable support material was used to accommodate the long slender parts being printed in this fashion. The parts were printed solid with 100% infill and layer thicknesses of 254 microns. The unpolished

batch of tensile specimens consist of five parts for each thickness, for a total of 15 parts. The support material was dissolved in caustic soda, then after the conditioning periods described below, pre-experiment dimensional measurements of each part were taken using a digital caliper after environmental conditioning explained below.

A Veeco Dektak 150 profilometer was utilized in order to reveal the surface topology of the tensile specimens. A typical contact profilometer uses a stylus to contact a specimen and then move laterally across the surface to register the profile changes in the vertical direction. The Veeco Dektak 150 used has a stylus with a radius of 12.5 µm and a resolution of 278 nm. For this study, profilometry scans were oriented along the z-direction of the parts with a scan length of 5 mm in 60 seconds with 10 mg of contact force. All samples were measured to find the average RMS roughness of the "as printed" unpolished parts.

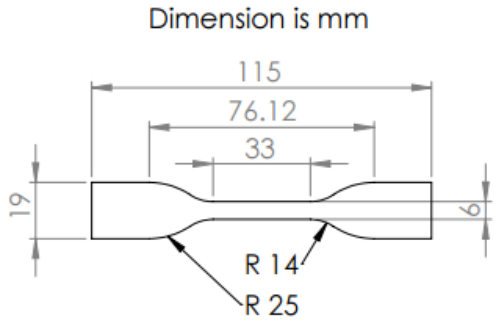

Figure 1: Dimensions of tensile specimens

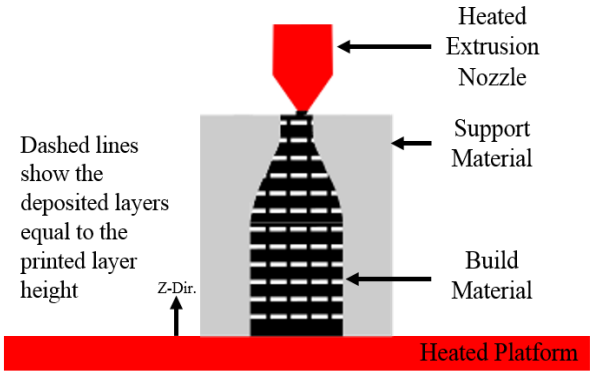

Figure 2: Build orientation of a tensile specimen showing the dashed deposition lines and surrounding support material

Three to five samples of each thickness were printed and then set aside to be vapor polished. The vapor polishing was done on three samples (one of each thickness) at a time. Two napkins of the same size were soaked with 5 ml of acetone and placed around the perimeter inside a 1 L (32 oz.) high-density polyethylene container. The tensile specimens were hung from a metal fixture inside the container and the container was sealed for 45 minutes. Figure 3 shows a schematic of the vapor polishing method. The polished parts were allowed to completely dry for 5 days (120 hours) under ASTM D618 procedure A conditioning requirements. Five days was allotted for drying to ensure the acetone evaporated out of the polished tensile specimens before testing. Figure 4 shows the mass of a sample 4 mm tensile specimen over time. The average (with standard deviation) weight gain is likely due to residual acetone or water vapor for the different thicknesses: 4 mm specimens have an average of 1.06% (St. Dev. of 0.003) weight gain [g], 2 mm specimens have an average of 2.83% (St. Dev. of 0.004) weight gain [g], and the 1 mm specimens have an average of 5.43% (St. Dev. of 0.005) weight gain [g]. Absolute weight gain is similar for all part thicknesses which is consistent with a surface-mediated process. Profilometry and dimensional measurements using a digital caliper were performed again on the post-processed barbells for later comparison of dimensional changes as well as changes in surface finish.

Finally, the specimens were mechanically tested in an MTS 858 hydraulic table-top tensile testing unit after conditioning the tensile specimens in accordance to ASTM D 618 Procedure A:

40/23/50 for specimens ≤ 7 mm (0.25”). The procedure calls for the standard laboratory atmosphere of 23°C ± 2° and 50% ± 10% relative humidity to condition the test specimens for a minimum of 40 hours [17]. The 40 hours minimum was applied for unpolished samples but at least 120 hours was applied to the polished samples to allow for evaporation of the acetone as discussed above. The testing was done in accordance to the ASTM Standard D638–10 [15]. Force, displacement, and strain data were collected in real time for later comparison.

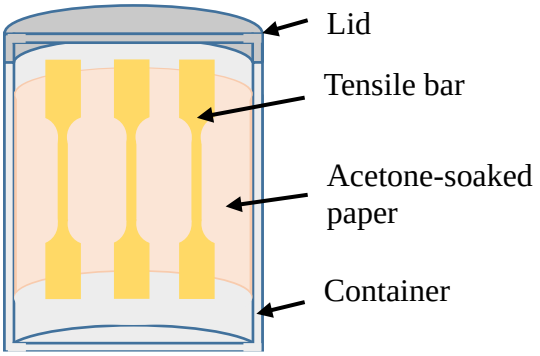

Figure 3: Vapor polishing station for tensile specimens

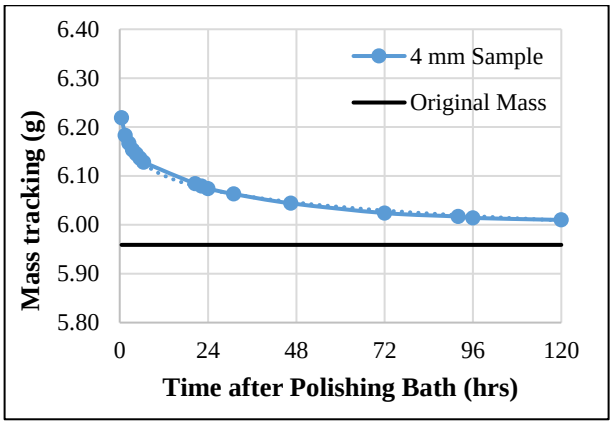

Figure 4: Mass of a post-processed sample over time

Results

Dimensional Changes

Table 1: Average absolute (measured) dimensional changes for vapor polished specimens

Geometry	1 mm sample	2 mm sample	4 mm sample
Δ Thickness (mm)	-0.01 ± 0.00	0.02 ± 0.00	0.03 ± 0.02
Δ Length (mm)	-0.82 ± 0.07	-0.22 ± 0.08	0.02 ± 0.04
Δ Width (mm)	-0.20 ± 0.07	-0.06 ± 0.60	0.06 ± 0.02

Table 2: Average percentage change of dimensional changes for vapor polished specimens

Geometry	1 mm sample	2 mm sample	4 mm sample
Δ Thickness (%)	-0.57 ± 0.41	0.96 ± 0.01	0.66 ± 0.42
Δ Length (%)	-0.71 ± 0.06	-0.19 ± 0.07	0.02 ± 0.03
Δ Width (%)	-4.42 ± 1.87	1.49 ± 1.38	0.80 ± 0.49

Ideally, post-processing shouldn’t alter the geometry or dimensions of the manufactured part. To assess the dimensional impact, dimensional data of the tensile specimens were taken before and after vapor polishing was introduced. Each measurement was repeated at least 3 times at different locations for thickness, width, and length. Table 1 below shows the measured dimensional changes recorded for pre and post-polishing of the samples meanwhile Table 2 depicts the percentage change for the dimensional changes. Table 1 and Table 2 indicate the change of

thickness is negligible with less than 1% change for the different thicknesses. The length change of the specimens is negligible, meaning that the 45 minute polishing duration is short enough to prevent slumping of the geometry due to the gravitational forces pulling material to the bottom end of the specimen. The only significant change in dimensions appears in the percentage change for the width of the 1 mm specimen. This suggests there may be a small surface effect resultant from smoothing of the bulging layer extrusions. The surface erosion acts more on the 1 mm samples as it effects a larger percentage of the width. Since most of the dimensional changes are less than 1%, the changes remain within the tolerance threshold of the uPrint machine.

Surface Roughness

One of the key parameters of this study evaluates the surface roughness of vapor polishing ABS FDM components. Figure 5 shows an FFT analysis of the surface roughness along the z-direction; this figure shows one sample before and post-processing. In each case, there is a peak corresponding to ~ 3.75 mm^{-1}, or ~ 254 µm (the characteristic layer thickness). The difference between the unpolished and polished samples show there was a 10X reduction in the frequency band corresponding to the layer thickness noise and a significant reduction at all dimensions that were apparent in the unpolished sample. Figure 6 below shows SEM photographs of unpolished vs. polished tensile specimens for the various thicknesses. The SEM photos show the substantial impact vapor polishing has on the surface roughness. The unpolished samples have peaks and valleys at each new deposition layer (254 µm layer). However, the polished samples show a large reduction in the artifact. Table 3 shows that polishing sharply decreased RMA surface roughness and variation in the surface roughness.

Table 3: Average roughness changes of post-processed specimens

	As-printed (µm)	Vapor polished (µm)
$R_a \pm$ St. Dev.	37.18 ± 14.55	10.13 ± 8.23
$R_q \pm$ St. Dev.	44.41 ± 15.06	12.39 ± 8.86

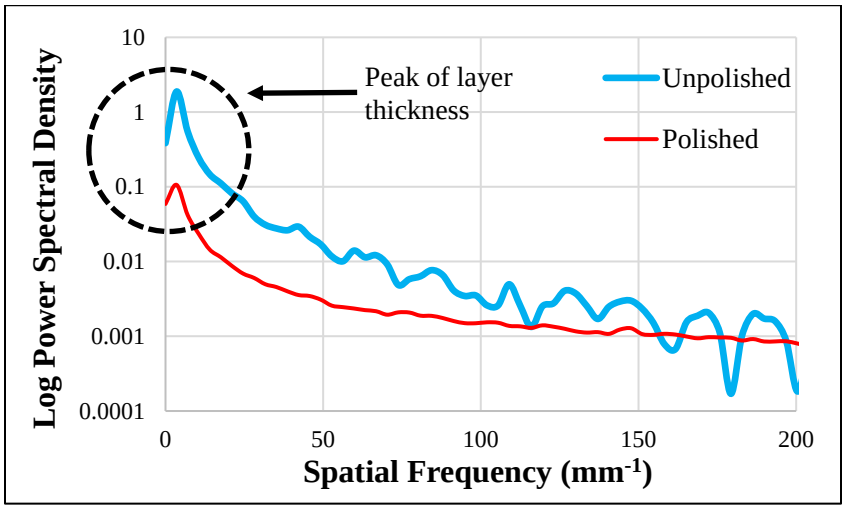

Figure 5: FFT analysis of a sample specimen for the surface roughness along the build orientation (z-direction)

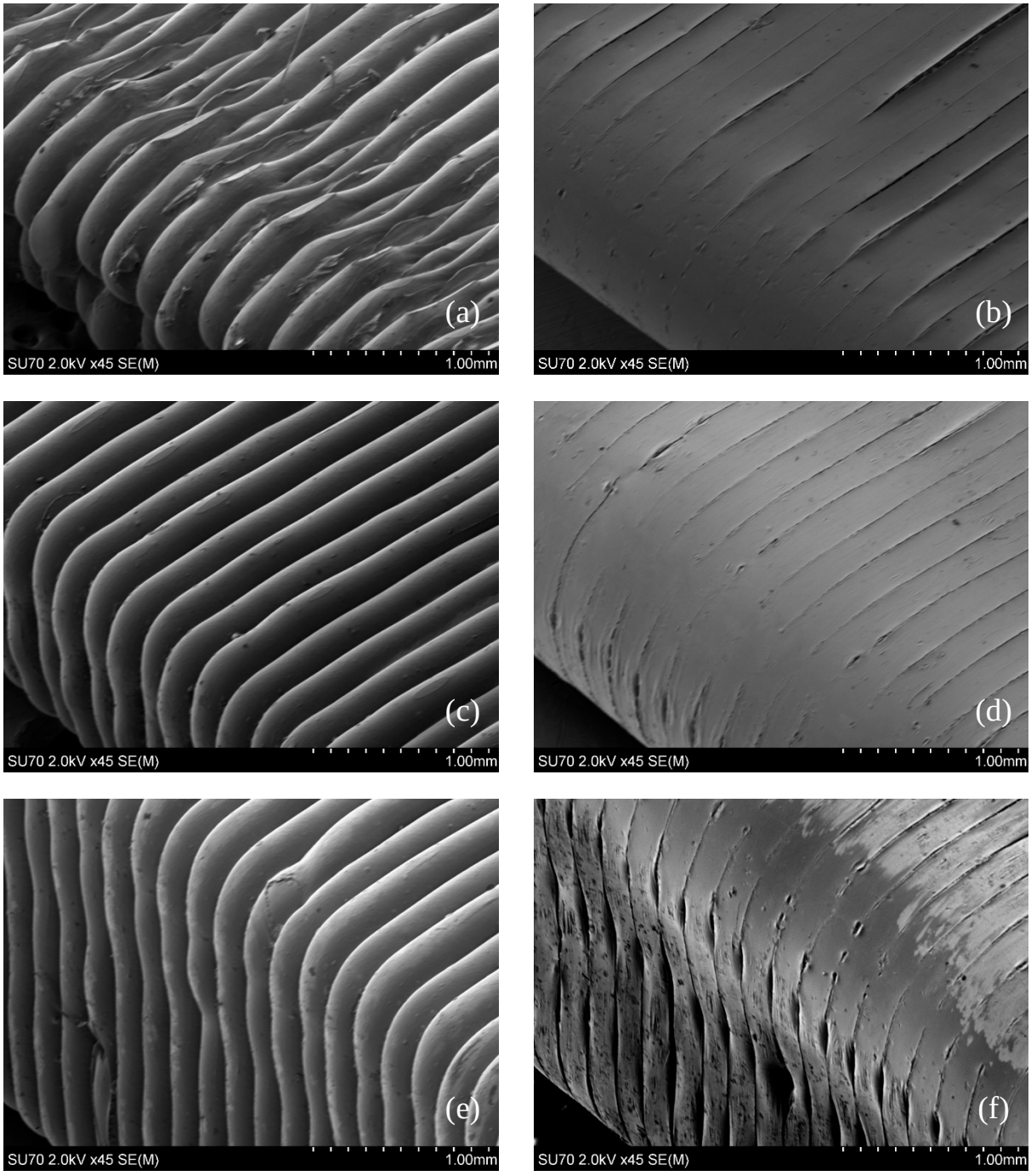

Figure 6: SEM of: 1 mm unpolished (a), 1 mm polished (b), 2 mm unpolished (c), 2 mm polished (d), 4 mm unpolished (e), 4 mm polished (f)

Mechanical Properties

Figure 7 shows the strain to failure, elastic modulus, and ultimate tensile strength vs. thickness with a sample stress vs. strain chart. No significant strength differences were observed between the polished and unpolished samples, however the strain to failure of the polished samples was higher than the unpolished (the difference falls within one standard deviation for all parts except the 2 mm thick parts). The strain to failure for the 1 mm polished specimens have the largest increase, but the elastic modulus has the largest decrease. Polishing has reduced the elastic modulus in all specimens, but the effect decreases with increasing thickness. The sample stress vs. strain chart supports this comparison as well. The 1 mm polished specimen also has more elongation and even a little yielding before fracture, but a lower value in slope (elastic modulus).

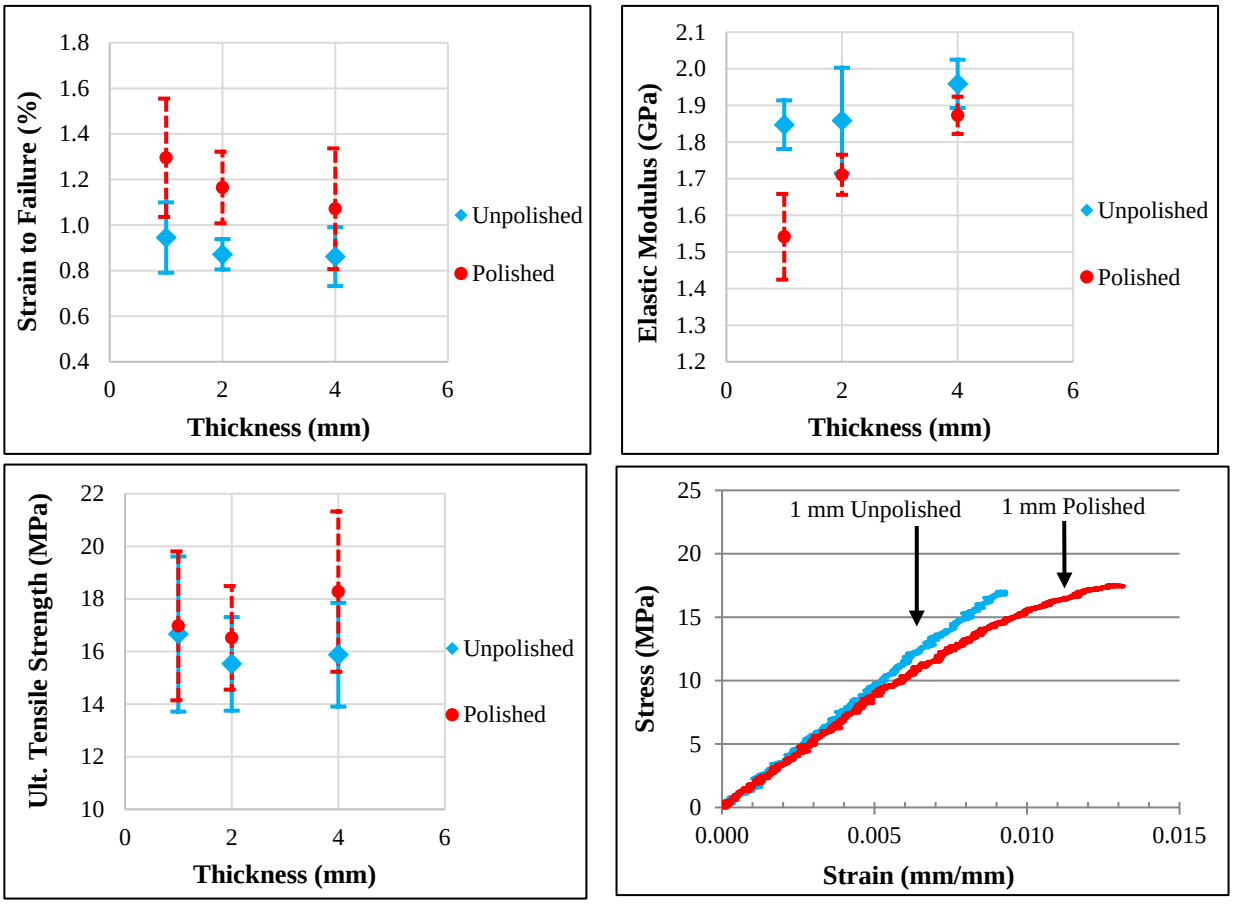

Figure 7: Mechanical property charts for unpolished vs. polished samples: strain to failure vs. thickness (top left), elastic modulus vs. thickness (top right), ult. Tensile strength (bottom left), stress vs. strain curves (bottom right)

Discussion

Acetone vapor polishing has a noticeable effect on the dimensional characteristics of ABS components of 1 mm thickness but negligible as the thickness increases. However, the noticeable effect could be minimized if the duration for polishing is reduced for thinner parts or less solvent is used. The outer texture of FDM parts have small rounded ridges that bulge out on each layer

from the cylindrical extrusion being flattened. Acetone vapor polishing partially dissolves some of this material on the surface of the part and allows the “high” material to flow into the “low” areas between each layer under surface tension effects. Gravitational and surface energy effects can both contribute to the material flows, especially as the viscosity decreases with increased acetone exposure. In general, if the acetone vapor polishing was done completely, one would think the final location of the surface would be somewhere close to the middle of the high and low points. However, the resulting dimensional change is insignificant for most applications. This is a desired result of any post-processing method.

Acetone vapor polishing has a profound effect on the surface finish of an ABS part. The average roughness and RMS roughness were both decreased significantly due to acetone vapor polishing. The sole purpose of this effect allows ABS FDM parts to have a smooth surface finish and be more aesthetically appealing to the eye instead of a rough granular one. For surface finish and dimensional tolerances, careful consideration needs to be taken as to the duration of polishing; over-polishing will distort the surface and cause tolerance issues. The process outcomes depend on the total acetone available, surface area of the parts, exposure time, and container volume. Further work is needed to characterize the relationship between the process parameters and the surface roughness outcomes.

Vapor polishing also affects the mechanical properties of ABS FDM parts. In general, the polished specimen strength is comparable (though slightly higher) than the unpolished specimens, and the elongation to break is increased. This is a desired effect that is hard to obtain with most traditional materials. Thinner components see a larger impact (ductility increased and reduced modulus of elasticity) than their thicker counterparts. This result is most likely due to the relatively larger surface area/volume ratio of the thinner specimens. The property change could be due to the shape change, but we believe it is likely related to the residual weight gain of the treated parts. The additional weight may be due to absorption of a plasticizing agent. A plasticizer by definition defines a low molecular weight polymer additive that enhances flexibility and workability but reduces stiffness. [18] In terms of this study the weight gain – either acetone, water vapor, or both – may be acting as plasticizer molecules to occupy interstitial positions between the larger polymer molecules. This would effectively increase the inter-chain distance between the larger polymer molecules. An increase in inter-chain distance would allow further elongation – thus strain before failure – but also comes with the penalty of reducing the intermolecular bonding, thus resulting in lower elastic modulus.

An interesting result to note appears in the trends of the ultimate tensile strength of polished versus unpolished specimens. As mentioned earlier, the 1 mm specimens achieve the highest strength value for unpolished samples but in opposition the 4 mm specimens achieve the highest strength value for polished samples. A possible solution to explain this trend may be the print time between each layer as the tensile specimens were printed in batches of same thickness. Therefore, the time between layers for thicker parts will be longer since the extrusion head has a longer deposition path to follow before it finishes a layer on each specimen. This translates to each layer having longer time to cool resulting in a decrease of adhesion between each layer. On the contrary, thinner specimens would have less time to cool between each layer resulting in greater bond strength. Since the adhesion of each new layer would integrate more into the previous layer, the thinner specimens would be able to reach higher stress levels. Vapor polishing erases this trend as

the adhesion between each layer during printing becomes less of a factor by intertwining the polymer chains of new layer together; resulting in higher achievable stress levels for thicker specimens.

The orientation of the z-direction was chosen for the printed tensile specimens as this is typically the weakest direction and thus the one most likely to benefit from post-processing. Because of the orientation of the printed parts during testing, they essentially have small cracks between each layer oriented normal to the force. This allows brittle fracture to occur as a result of mode I crack opening failure. Acetone vapor polishing fills the cracks on the outside – and depending on the thickness, the whole part – with dissolved material, either shortening the crack length or eliminating the cracks completely. This should result in better mechanically-performing parts, however this effect was insignificant in these tests. It seems unlikely that there would be an impact in other printing orientations.

This work considered only the case for a full infill. Parts with partial infill may behave very differently as there are many more interfaces to bond. This may create new opportunities for property enhancement through vapor polishing. Partial infill may also introduce new failure mechanisms as thinner surface sections may collapse with excessive acetone.

In general, more data needs to be collected, and variations of the post-processing methods (especially those that vary the strength) need to be further explored to determine what the ideal post-processing parameters should be in order to obtain better looking parts that have bulk-like mechanical properties, but still maintain dimensional tolerance.

Conclusions

AM-printed FDM components have obvious drawbacks of surface roughness and anisotropic properties. This study investigates the effect of post-processing ABS tensile specimens by subjecting them to vapor polishing in an effort to improve on the drawbacks. Vapor polishing decreases surface roughness vastly while also having an impact on mechanical performance. It was found that vapor polishing has a larger impact on thinner components by increasing strain to failure and strength but decreasing the elastic modulus. Thicknesses above 2 mm show a modest improvement in ductility and strength with a modest decrease in elastic modulus. This study helps to improve the quality of ABS FDM components and with future work can ultimately advance FDM technology.

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