Faculty Publications

2018

Impact of Vapor Polishing on Surface Quality and Mechanical Properties of Extruded ABS

Clayton Neff

Matthew Trapuzzano

Nathan B. Crane

Brigham Young University - Provo, nbcrane@byu.edu

Follow this and additional works at: <https://scholarsarchive.byu.edu/facpub>

Part of the [Other Mechanical Engineering Commons](#)

Original Publication Citation

Clayton Neff, Matthew Trapuzzano, and N. B. Crane, "Impact of Vapor Polishing on Surface Quality and Mechanical Properties of Extruded ABS", *Rapid Prototyping Journal*, v 24 No 2, 2018.

BYU ScholarsArchive Citation

Neff, Clayton; Trapuzzano, Matthew; and Crane, Nathan B., "Impact of Vapor Polishing on Surface Quality and Mechanical Properties of Extruded ABS" (2018). *Faculty Publications*. 5350.
<https://scholarsarchive.byu.edu/facpub/5350>

This Peer-Reviewed Article is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in Faculty Publications by an authorized administrator of BYU ScholarsArchive. For more information, please contact ellen_amatangelo@byu.edu.

Impact of Vapor Polishing on Surface Quality and Mechanical Properties of Extruded ABS

1. Abstract

Purpose — Additive manufacturing (AM) is readily capable of producing models and prototypes of complex geometry and is advancing in creating functional parts. However, AM processes typically underperform traditional manufacturing methods in mechanical properties, surface roughness, and hermeticity. Solvent vapor treatments (vapor polishing) are commonly used to improve surface quality in thermoplastic parts, but the results are poorly characterized.

Design/methodology/approach — This work quantifies the surface roughness change and also evaluates the effect on hermeticity and mechanical property impacts for “as-printed” and acetone vapor-polished ABS tensile specimens of 1, 2, and 4 mm thicknesses produced by material extrusion (FDM).

Findings — Vapor polishing proves to decrease the power spectral density for surface roughness features larger than 20 μm by a factor of 10X, and shows significant improvement in hermeticity based on both perfluorocarbon gross leak and pressure leak tests. However, there is minimal impact on mechanical properties with the thin specimens showing some increase in elongation at break but decreased elastic modulus. A bi-exponential diffusion decay model for solvent evaporation suggest a thickness independent and thickness dependent time constant with the latter supporting a plasticizing effect on mechanical properties.

Originality/value — The contributions of this work show vapor polishing can have a substantial impact on the performance for end-use application of ABS FDM components.

Keywords Vapor polishing, surface roughness, hermeticity, mechanical properties, bi-exponential diffusion decay, FDM, additive manufacturing

Paper type Research paper

2. Introduction

Additive manufacturing (AM) refers to a group of processes that create parts directly from digital models (Sachs, 1992, Jacobs, 1992). Typically, AM processes stack layers produced by 2D processes, such as inkjet printing. AM can create highly complex parts of near arbitrary geometry with less lead time and lower customization costs by eliminating part-specific tooling (Gibson, 2010, Gebhardt, 2012).

Thermal extrusion technologies are low-cost AM systems that feed thermoplastic material into a heated extrusion head (Turner, 2014) and deposits it through a nozzle that moves under computer control (Stevens, 1995). It was first developed by Stratasys (Crump, 1992). While the process is conceptually simple, it has limitations arising from the pointwise fabrication process. The final mechanical properties such as strength and elongation to failure are typically reduced relative to traditional manufacturing processes and highly dependent on build orientation and other process parameters (Ahn, 2002, Ashtankar, 2013, Raut 2014, Bellini, 2003). Reduced strength, stiffness, and ductility likely originate from the discrete stacking of cross-sectional layers, which creates stress concentrations and weaker internal bonding that are not present in a traditional manufacturing process. The pointwise deposition also introduces surface defects and micro-porosity due to imperfect material bonding and process errors (Agarwala, 1996). The porosity (even on the micro-scale) reduces strength of the printed parts (Santhakumar, 2016) and leaves fluid passages that impede sealing required in fluidic channels and electronic packaging (Au, 2016). A layer-by-layer extrusion process inherently produces much rougher surfaces when comparing traditional manufacturing processes, another limiting factor for extrusion AM.

To improve surface finish, many parts are mechanically polished or coated to improve the surface. Mireles and Cater show coating or vacuum infiltrating with epoxies and a variety of sealants can reduce leakage through pressurized acrylonitrile butadiene styrene (ABS) FDM parts at low-pressures, but these methods can generate non-uniform surfaces (Mireles, 2011, Cater, 2014). Vapor polishing is another post-processing alternative for ABS (Benchoff, 2013, Frick, 2014) which provides a low-labor process compared to mechanical polishing and coating. In a typical vapor polishing treatment, a part is exposed to a solvent vapor (typically acetone for ABS) that absorbs into the surface layer of the part—reducing the surface viscosity. In a process similar to viscous sintering, the high peaks of surface roughness “flow” into the valleys of the surface roughness driven by surface tension. This produces a smoother, shinier surface finish, Figure 1. In prior work on thermoplastic parts, controlled solvent exposure has shown to improve strength of weld-lines when joining ABS geometries (Brewer, 1987) and a chemical finishing process for laser-sintered Nylon parts was shown to significantly improve ductility in addition to reducing surface roughness (Crane, 2017).

Vapor polishing reduces surface roughness with the potential to maintain dimensional accuracy and preserve part geometry (Espalin, 2009, Turner, 2015, D.M., 1985, Garg, 2015). Singh showed that vapor smoothing at elevated temperatures reduced surface roughness and marginally increased hardness (Singh, 2016). However, the bulk properties and the effects of part thickness were not quantified. Additionally surface smoothing, mechanical property impacts, and hermeticity of room temperature vapor polishing have not been reported. This paper measures the impacts of acetone vapor polishing of ABS parts on the mechanical properties (strength, elastic modulus, elongation to break, energy absorption), surface roughness, and hermeticity. This provides critical information to those considering vapor polishing with respect to both the surface finish improvements and the impact on mechanical properties as a function of thickness.

Figure 1: Vapor polishing process

3. Experimental Methods

3.1 Tensile Specimens

Tensile specimens consistent with ASTM Standard D638–10 Type IV (ASTM, 2010) were fabricated on a Stratasys uPrint SE machine in ABS Plus material with various thicknesses of 1, 2, and 4 mm with dimensions shown in Figure 2a. The parts were printed with the longitudinal axis oriented in the z-direction (normal to the print bed) in the ZXY plane – as designated by ASTM F2921 (ASTM, 2011) and illustrated in Figure 2b. The tensile axis of the specimens was aligned to the z-direction to maximize sensitivity to

mechanical property improvements during post-processing because the z-direction typically has the highest surface roughness and weakest bond strength in FDM (Ashtankar, 2013, Bellini, 2003, Raut 2014). The parts were printed with 100% infill and layer thicknesses of 254 μm . Ten parts were printed for each thickness and divided into treated and untreated controls. After removing support material in caustic soda, the parts were conditioned following ASTM D618 Procedure A at $23^\circ\text{C} \pm 2^\circ$ and $50\% \pm 10\%$ relative humidity for a minimum of 40 hours (ASTM, 2013). The as-printed dimensions of each part were measured using digital calipers. Each measurement was repeated at least 3 times at different locations.

Surface roughness of all parts were measured using a Veeco Dektak 150 profilometer with a tip radius of 5 μm and a spatial resolution of 8 and 0.278 [nm] in the vertical and horizontal direction, respectively. Profilometry scans were oriented along the “z” printing axis with a scan length of 5 mm in 60 seconds and 10 mg of contact force. The average and RMS roughness of the “as printed” unpolished parts were calculated for comparison. Profilometry data was transformed into the frequency domain with a fast fourier transform (FFT) to provide insight of the spatial frequency for different surface features over a significant length scale.

The tensile specimens were tested in an MTS 858 hydraulic table-top tensile testing unit after conditioning the tensile specimens in accordance to ASTM D 618 Procedure A. The tensile testing was done in accordance to the ASTM Standard D638–10 (ASTM, 2010) with a strain rate of 0.5 mm/min. Force, displacement, and strain data were recorded.

Figure 2: (a) Dimensions of tensile specimens and (b) build orientation of tensile specimens showing different thicknesses of the specimens

3.2 Vapor Polishing

Vapor polishing was done on the treated control group using three samples (one of each thickness) at a time. Two napkins of the same size were soaked with 5 ml of acetone each and placed around the perimeter of a 1 L high-density polyethylene container. The tensile specimens were suspended from a metal fixture inside the container and the container was sealed for 45 minutes. The polished parts were allowed to dry for 5 days (120 hours) under ASTM D618 Procedure A conditioning requirements. After five days, a residual weight gain was still observed, as seen in Figure 3. The weight gain is likely due to residual acetone or water vapor. Weight gain is similar for all part thicknesses which is consistent with a surface-mediated process.

Figure 3 shows that mass change over time is consistent with a bi-exponential decay diffusion model. A bi-exponential decay diffusion model suggests two separate time constants representing different physical kinetics in a parallel process. The first time constant suggest there is a sharp evaporation of the acetone initially due to the solvent vapor evaporating from the surface layer quickly after removal from the vapor bath. The time constant of this first step is similar for all part thicknesses. The slower time constant is

sample thickness dependent suggesting that it may be dependent on the vapor transport through the plastic to the surface. Mass tracking shows the residual weight gain slightly changes material composition, which may be a concern for certain applications. Profilometry and dimensional measurements were repeated on the vapor-polished barbells.

Figure 3: Mass tracking of residual weight gain of vapor-polished samples for different thicknesses over time

3.3 Hermeticity Specimens

Hermeticity test specimens were designed with a flange on the bottom with a centered hemisphere on top with an internal cavity of 0.23 cm³ to be able to compare gross leak hermeticity methods (MIL-STD-883E-1014.9 – Seal, Hermeticity Condition 1) and internal pressurization methods similar to Mireles', et al. approach testing sealant and epoxy coatings/vacuum infiltrations of ABS AM extrusion components (Mireles, 2011). Figure 4 below shows the hermetic test specimens. The hemisphere thickness was varied with nominal values of 0.8, 1.0, 1.2 and 1.6 mm. All hermeticity parts were printed in ABS material on an open source RepRap printer.

In the prior work, a multi-feature test part was designed with an internal cavity and attached to a test fixture with a pressure inlet to pressurize the internal cavity (Mireles, 2011). Results show a few sealants and epoxies can eliminate visible bubbling up to 140-275 kPa (20-40 psi) internal pressure, but many of the sealants and epoxies leaked—even for pressures below 70 kPa (10 psi). The current work applied the same testing strategy for the vapor polishing study using the experimental setup illustrated in Figure 5. Prior to water submersion testing, a hole was drilled in the bottom of the hermetic test specimen to allow for pressurization of the internal cavity. The specimen was clamped between the top and bottom fixture and then submerged in water. Pressure was ramped at a rate of 35 kPa/min (5 psi/min) until the max pressure of 345-415 kPa (50-60) psi was reached. If bubbles failed to emanate on the part surface, during the pressure ramp, the specimen passed.

Batches of hermeticity specimens were vapor polished following the tensile bar procedure and conditioned for five days according to ASTM D 618 Procedure A before testing. Figure 4 demonstrates the significant smoothing impact of vapor polishing on the surface of the hermeticity specimens.

Figure 4: Printed specimens for hermetic testing: (a) unpolished sample, (b) vapor polished sample, (c) 0.8 mm dome thickness cross section, (d) 1.6 mm dome cross section

Figure 5: (a) Diagram of pressure leak experimental setup, (b) machined bottom fixture with O-rings and sample specimen, and (c) mounted top plate with specimen in center

Hermetic test specimens were also subjected to a perfluorocarbon gross leak test specified by MIL-STD-883E-1014.9 – Seal, Hermeticity Condition 1 to validate and compare the results of the air pressurization test. This test determines the effectiveness (hermeticity) of the seal of microelectronic and semiconductor devices with designed internal cavities (MIL-STD, 1996).

The MIL-STD test method was modified slightly from standard procedures to accommodate the temperature limits of the printed structures. The perfluorocarbon fluids used in this study were 3M Fluoroinert FC-72 for Type 1 detector fluid and 3M Fluoroinert FC-40 for Type 2 indicator fluid and abide by the physical property requirements specified by the MIL-STD. (MIL-STD, 1996) Figure 6 illustrates the MIL-STD procedures for the printed test specimens. As the test specimens had a nominal internal volume of 0.23 cm^3 , a long vacuum exposure wasn't required. However, they were conditioned by 30 minutes under

vacuum at $P < 5$ torr prior to testing to help remove any absorbed moisture or other contaminants. Then the parts were returned to atmospheric pressure and immediately prepped for testing.

The Type 1 detector fluid and test samples were placed in a vacuum chamber and the pressure reduced below 5 torr for a minute before submerging the specimens in the Type 1 detector fluid. Pressure was held for one minute before returning to atmosphere. The specimens were then placed under 310 kPa (45 psi) for 8 hours. When the samples were removed from the bath they were dried for 2 ± 1 minute in air prior to immersion in Type 2 indicator fluid, maintained at 100°C . This is reduced from the specification of 125°C due to concern for the softening of the ABS specimens. Since 100°C is still well above the Type 1 FC-72 detector fluid's boiling point (56°C), the detector fluid still formed bubbles when present. Devices remained immersed at a minimum depth of 50 mm below the surface of the indicator fluid and observed for bubble emanation for a minimum of a 30 second observation period. If a definite stream of bubbles or at least two large bubbles originate from the same point the part is considered to have failed the test.

Figure 6: Perfluorocarbon gross leak test

4. Results

4.1 Dimensional Changes

Table 1: Average dimensional changes for vapor polished tensile 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

Ideally, post-processing shouldn't alter the geometry or dimensions of the manufactured part. Table 1 summarizes the dimensional changes after vapor polishing. The change of thickness and length are negligible with less than 1% change for each specimen thickness. This suggests 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 width—particularly of the 1 mm specimen. This suggests there may be a small surface effect resultant from smoothing of the bulging layer extrusions. Polishing has more impact on the 1 mm samples as more of the material is in the surface affected region. Most of the dimensional changes remain within the tolerance threshold of the uPrint machine.

4.2 Surface Roughness

The key motivation for using vapor polishing is to reduce the roughness, but little data has been produced on the impact of polishing on the surface roughness. Figure 7a compares the profilometry data for a representative polished and unpolished sample. Roughness is dramatically reduced (72% for both R_a and R_q) as evidenced by scan statistics in Table 2 as well. Garg and Singh both found similar large reductions in roughness when vapor polishing, but with lower average (R_a) and RMS (R_q) surface roughnesses (Singh, 2016, Garg, 2015). However, this is expected since the prior work didn't scan along the coarsest direction (normal to the print bed), and Garg et al. used a thinner layer height while printing. An FFT analysis of the surface roughness along the z-direction (Figure 7b) shows there is a strong peak corresponding to the layer thickness as $\sim 3.75 \text{ mm}^{-1}$ or $\sim 254 \mu\text{m}$. The power spectral density of the polished specimen is reduced 10X relative to the unpolished specimens at the layer height and is reduced significantly at nearly all length scales. This is supported by SEM images of treated and untreated surfaces as seen in Figure 8. The unpolished samples have clear peaks and valleys at each layer which are nearly eliminated by polishing though some sharp edges remain at the layer boundaries.

Figure 7: (a) Profilometry data of the surface roughness long the build orientation (z-direction), (b) FFT analysis of a sample specimen for the surface roughness along the build orientation (z-direction)

Table 2: Average roughness changes of post-processed specimens

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

Figure 8: SEM of: (a) 1 mm unpolished, (b) 1 mm polished, (c) 2 mm unpolished, (d) 2 mm polished, (e) 4 mm unpolished, (f) 4 mm polished

4.3 Mechanical Properties

Mechanical testing results are summarized in Figure 9. The sample stress/strain data (Figure 9a) of a 2 mm polished specimen shows increased elongation before fracture, but a decrease in elastic modulus. Despite the reduced surface defects, significant strength differences were not observed between the polished and unpolished samples. While the strain to failure of the polished samples was higher than the unpolished, the

difference falls within one standard deviation for all 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. Stress vs. strain curves of Figure 9a show a significant increase in the energy absorbed to fracture in the polished sample. Table 3 shows there is about a 50 – 60% increase in energy absorption across all thicknesses.

Figure 9: Mechanical property charts for unpolished vs. polished samples: (a) stress vs. strain curves for 2 mm thick samples, (b) Ultimate tensile strength, (c) strain to failure, (d) and elastic modulus vs. sample thickness

Table 3: Energy absorption [units in kJ/m³]

Sample Thickness (mm)	Unpolished	Polished	Percentage Increase
1	83.04 ± 27.87	126.01 ± 43.08	51.75
2	70.48 ± 12.73	112.18 ± 24.91	59.17
4	76.19 ± 18.27	113.14 ± 42.89	47.50

4.4 Hermeticity

Hermetic testing results in Table 4 shows vapor polishing can have a profound effect on alleviating surface porosity and achieving a gross hermetic seal for ABS FDM components. For the air pressurization test, all of the vapor polished UFO specimens for different thicknesses passed hermeticity except one. This specimen may have been damaged during test preparations (i.e. poking a small hole while drilling the pressure inlet). All of the unpolished UFO specimens with less than 1.6 mm in hemi-sphere thickness failed hermeticity though a majority of the 1.6 mm unpolished UFO specimens passed. At high infill levels, the overlapping layers improves sealing with increased thickness as expected. Most of the vapor polished specimens for hermeticity pass the perfluorocarbon gross leak test while all of the as-printed specimens fail.

Legend
✓ = passed
○ = failed

Table 4: Hermetic testing results

Hemi-sphere thickness (mm)	Perfluorocarbon gross leak test		Air pressurization test	
	Unpolished	Polished	Unpolished	Polished
0.8	○ ○ ○ ○	✓ ✓ ✓ ○	○ ○ ○ ○	✓ ✓ ✓ ○
1.0	○ ○ ○ ○	✓ ✓ ✓ ○	○ ○ ○	✓ ✓ ✓
1.2	○ ○ ○ ○	✓ ✓ ✓ ✓	○ ○ ○ ○	✓ ✓ ✓ ✓
1.6	○ ○ ○ ○	✓ ✓ ○ ○	✓ ✓ ✓ ○	✓ ✓ ✓

5. Discussion

Acetone vapor polishing has a substantial impact on the surface finish of the treated ABS parts. The acetone vapor polishing partially dissolves some of the outward bulging 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. The average and RMS roughness both decreased significantly (72%) due to vapor polishing creating a visibly smooth and shiny surface finish that is more aesthetically appealing than the as-printed parts. Vapor polishing also seems to heal minor process defects on the surface. For example, the SEM imaging comparison of the 1 mm tensile specimens in Figure 8a and Figure 8b shows the as-printed specimen to have a process error from the extrusion deposition but the 1 mm vapor polished specimen largely erases this artifact. The present tests show that vapor polishing can have a small effect on the dimensional characteristics of ABS components of 1 mm thickness but is negligible at larger thicknesses. However, the dimensional changes are dependent on the processing parameters and part geometry. Further work is needed to characterize the relationship between the process parameters and the surface roughness outcomes.

Unlike chemical treatments for Nylon laser-sintered parts (Crane, 2017), vapor polishing of ABS FDM parts had a very small impact on the mechanical properties except energy absorption. In general, the polished specimen strength is comparable with the unpolished specimens. While the elongation to break is increased, it remains much lower than injection molded ABS. Thinner components are impacted more than their thicker counterparts. This result is most likely due to the relatively larger surface area/volume ratio of the thinner specimens. The small elastic modulus and elongation to failure changes could be due to the surface smoothing itself, but we believe it is likely related to the residual weight gain of the treated parts. The additional weight may be due to retention of residual acetone that acts as a plasticizer—enhancing ductility but reducing stiffness (Callister Jr., 2010). Vapor polishing enhances the energy absorption and ductility of the printed parts substantially, but still well below injection molded ABS since the failure is interlaminar brittle fracture.

The z-direction printing orientation was chosen for the tensile specimens as this is typically the weakest direction and thus the one most likely to benefit from post-processing. The layer boundaries create small cracks between each layer oriented normal to the force where high stress concentrations can accumulate. This allows brittle fracture to occur as a result of mode I crack opening failure. Acetone vapor polishing partially fills the cracks on the outside, either shortening the crack length or potentially eliminating the cracks completely. This should result in better mechanically-performing parts, however the strength impact was insignificant in these tests even though the mechanical properties were tested in the worst case mechanical orientation due to interlaminar brittle fracture. This is likely because the smoothing effects were limited to the surface region due to the steep acetone concentration gradient. Since a significant strength change was not observed in this direction, it is unlikely that there would be an impact in other printing orientations with the current polishing process.

The SEM imaging of the vapor polished tensile specimens show there are still some sharp defects present at the layer boundaries after polishing. This suggests that the highest peaks of the surface roughness are flowing toward the recesses, but the material in the negative features is not dissolving and flowing. This may be due to rapid absorption of acetone at the exterior surface preventing effective acetone transport into the negative features required for full smoothing and complete crack healing. Without complete crack healing, stress concentrations are still present at the surface and in the interior which wouldn't allow for the increase in strength comparable to bulk material properties. A change in the vapor polishing method with enhanced diffusion of acetone uniformly into the surface of the specimen could enhance strengthening effects of extrusion components to compare more equally to bulk material properties. However, the layer to layer bonding may still remain a weakness.

Vapor polishing provides a novel approach for effectively sealing the inherent porosity of the extrusion process. The perfluorocarbon gross leak test seems to be a more demanding test for the printed parts than the internal pressurization test. This may be due to the different phenomenon at play during each test type. The water submersion test fails if the pressurized air is transported through the wall by a continuous channel. In contrast, the perfluorocarbon test detects the existence of any pores exposed to the exterior of the sample. Printed samples are likely to fail the perfluorocarbon test before the water submersion test because bubbles can emanate from surface porosity even if there is not a continuous path through the entire thickness of the material. Vapor polishing directly addresses this limitation since it acts at the exterior surface. Component sealing by vapor polishing can open applications of fluid pressure components, electronics packaging, or even medical device housings where the protection of internal components from the surrounding environment is critical.

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 exposure. Given the known potential for residual stresses in printed parts, vapor polishing may also introduce challenges with environmental stress cracking (ESC). While this has not been noted in the literature or observed in our tests, it may be an issue for future investigation.

6. Conclusions

FDM components have obvious drawbacks of surface roughness, porosity, and anisotropic properties. This study investigates the effect of vapor polishing of ABS tensile specimens on surface roughness, dimensional accuracy, mechanical properties, and porosity of the printed parts. Polishing significantly decreases surface roughness but has a modest impact on mechanical performance that decreases with increasing part thickness. 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. Energy absorptions increase is similar for all thickness levels. Vapor polishing largely eliminates the porosity of extruded components and effectively establishes a gross hermetic seal. This study helps to improve the quality of ABS extrusion components and with future work can ultimately advance extrusion technologies.

References

- Agarwala, M. K., Jamalabad, V.R., Langrana, N.A., Safari, A., Whalen, P.J., Danforth, S.C. (1996), "Structural quality of parts processed by fused deposition", *Rapid Prototyping Journal*, 2, 4-19.
- Ahn, S., Montero, M., Odell, D., Roundy, S., Wright, P.K. (2002), "Anisotropic material properties of fused deposition modeling abs", *Rapid Prototyping Journal*, 8, 248-257.
- Ashtankar, K. M., Kuthe, A. M., Rathour, B.S. Effect of build orientation on mechanical properties of rapid prototyping (fused deposition modelling) made acrylonitrile butadiene styrene (abs) parts. ASME International Mechanical Engineering Congress and Exposition, November 15–21, 2013 2013 San Diego, California, USA.
- ASTM 2010. D638 standard test method for tensile properties of plastics.
- ASTM 2011. F42 - f2921 standard terminology for additive manufacturing—coordinate systems and test methodologies.
- ASTM 2013. D618 standard practice for conditioning plastics for testing.
- Au, A. K., Huynh, W., Horowitz, L.F., Folch, A. (2016), "3d-printed microfluidics", *Angewandte Chemie International Edition*, 55.
- Bellini, A., Güçeri, S. (2003), "Mechanical characterization of parts fabricated using fused deposition modeling", *Rapid Prototyping Journal*, 9, 252-264.
- Benchoff, B. 2013. *Giving 3d printed parts a shiny smooth finish* [Online]. Available: <http://hackaday.com/2013/02/26/giving-3d-printed-parts-a-shiny-smooth-finish/>.
- Brewer, G. W. 1987. Technique for strengthening weldlines in thermoplastic parts. *ANTEC 87 Conference Proceedings - Society of Plastics Engineers 45th Annual Technical Conference & Exhibit*. Los Angeles, CA, USA: Soc of Plastics Engineers
- Callister Jr., W. D., Rethwisch, D. 2010. *Materials science and engineering an introduction*, John Wiley & Sons, Inc. .
- Cater, M. R. 2014. *Permeability and porosity reduction of fused deposition modeling parts via internal epoxy injection methods*. Master's Thesis, Ohio State University.
- Crane, N. B., Ni, Q., Ellis, A., Hopkinson, N. (2017), "Impact of chemical finishing on laser-sintered nylon 12 materials", *Additive Manufacturing*.
- Crump, S. 1992. *Apparatus and method for creating three-dimensional objects*. US 07/429,012.
- D.M., V. 1985. *Vaporous solvent treatment of thermoplastic substrates*. USA patent application US 06/553,647.
- Espalin, D., et al. 2009. Effects of vapor smoothing on abs part dimensions. *Rapid 2009 Conference and Exposition*. Schaumburg, IL, United states: Society of Manufacturing Engineers.
- Frick, L. 2014. *How to smooth 3d-printed parts* [Online]. Pentum. Available: <http://machinedesign.com/3d-printing/how-smooth-3d-printed-parts>.
- Garg, A., Bhattacharya, A., Batish, A. (2015), "On surface finish and dimensional accuracy of fdm parts after cold vapor treatment", *Materials and Manufacturing Processes*, 31.
- Gebhardt, A. 2012. *Understanding additive manufacturing*, Carl Hanser Verlag.
- Gibson, I., Rosen D.W., Stucker, B. 2010. *Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing*, New York, Springer.
- Jacobs, P. F. 1992. *Rapid prototyping & manufacturing, fundamentals of stereo lithography*, Dearborn MI, Society of Manufacturing Engineers.
- MIL-STD 1996. 883e-1014.9 - seal, hermeticity condition 1. *Test Method Standards - Microcircuits*. Department of Defense.

- Mireles, J., Adame, A., Espalin, D., Medina, F., Winker, R., Hoppe, T., Zinniel, B., Wicker, R. 2011. Analysis of sealing methods for fdm-fabricated parts. *Solid Freeform Fabrication Symposium*. Austin, TX.
- Raut , S., Jatti, V.S., Khedkar, N.K., Singh, T.P. (2014), "Investigation of the effect of built orientation on mechanical properties and total cost of fdm parts ", *Procedia Materials Science*, 6, 1625-1630.
- Sachs, E., Cima, M., Williams, P., Brancazio D., Cornie, J. (1992), "Three dimensional printing: Rapid tooling and prototypes directly from a cad model", *Journal of Engineering for Industry*, 114, 481-488.
- Santhakumar, J., Maggirwar, R., Gollapudi, S., Karthekeyan, S., Kalra, N. (2016), "Enhancing impact strength of fused deposition modeling built parts using polycarbonate material", *Indian Jouhrnal of Science and Technology*, 9.
- Singh, R., Singh, S., Singh, I.P. (2016), "Effect of hot vapor smoothing process on surface hardness of fused deposition modeling parts", *3D Printing and Additive Manufacturing*, 3.
- Stevens, M. J., Covas J.A. 1995. *Extruder principles and operation*, Dordrecht, Springer.
- Turner, B. N., Gold, S.A. (2015), "A review of melt extrusion additive manufacturing processes: Ii. Materials, dimensional accuracy, and surface roughness", *Rapid Prototyping Journal*, 21, 250-261.
- Turner, B. N., Strong, R., Gold, S.A. (2014), "A review of melt extrusion additive manufacturing processes: I. Process design and modeling", *Rapid Prototyping Journal*, 20, 192-204.