

3D Printing Surface-Finishing Agents



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Abstract—This paper examines and compares three methods used to improve the surface finish of plastic objects created using Fused Deposition Modeling: epoxy, acetone, and primer spray. We compared them using the two criteria most important to the widespread commercial adoption of 3D printing: surface finish results and effect on mechanical properties. In the first section, we present the state of the published literature regarding this topic; finding the literature lacking in comparison studies, in the second section we conduct our own test of the three methods on the two criteria, and then review the results. Finally, we discuss the merits of these three finishing agents in practical applications, based on all the information presented in the first two sections.

Index Terms— coatings, fused deposition modeling, manufacturing technology, materials processing, mechanical behavior

I. INTRODUCTION

The staircase effect, the ridged surface finish well-known to anyone familiar with 3D printing, is an undesirable side effect of the Fused Deposition Modeling (FDM) process. It is a hindrance to the mass acceptance of this manufacturing method, and can cause both sub-par aesthetics and functional issues such as increased friction between 3D printed components. This poor surface finish requires chemical or mechanical post-processing (and consequently cost and time) to correct. Acetone baths are one example of a chemical process that has been commonly used to smooth the surface of 3D-printed objects. Other techniques, which have not been as thoroughly studied, are epoxies, sprays, machining, and sanding or sandblasting. In this report we will compare 3D printing surface finishing techniques, on both their ability to improve the finish quality of the original printed part, and their effects to the mechanical properties. Specifically, we chose to compare epoxy, acetone, and primer sprays, because these three methods are chemicals applied to the surface of prints. Continuing research could deal with mechanical post-processing, like sanding or machining. More detail about each of the methods we chose, as they pertain to this topic, follows.

A. Epoxy

In the context of this report, “epoxy” refers to the method of coating a 3D print with epoxy resin in order to improve its surface finish. 3Dprint.com details how this is safer than methods using the potentially hazardous chemical acetone, and produces a glossy and smooth finish easily [1]. They recommend using a small paint brush to apply the epoxy to the surface of the print, but since our samples in Section III were cylindrical, we chose to roll them on a surface covered in

epoxy to attempt a more even coating.

B. Acetone

Many methods for 3D print smoothing involving acetone have been developed. Some use acetone vapor for a light application, some use it in liquid form for more corrosive power. Some involve chilling the prints so that the vapor condenses more readily on their surfaces; others involve heating the acetone in a chamber to create more vapor, which can be hazardous. In Section II we will discuss literature that pertains to various acetone-involved methods, but in Section III we chose to perform our tests using a cold-vapor method with the samples and the acetone at room temperature for convenience and safety.

C. Primer Spray

There are several 3D printing finishing sprays currently being marketed, and still others being used off-label by the 3D printing community to improve surface finish. Since some of these are just spray forms of acetone [2], we decided to chose the spray that was most different from the other two methods above in order to avoid redundancy: primer spray. The literature was significantly lacking on this topic, so the tests in Section III were very informative. A tutorial by Sculpteo, a cloud 3D printing service, recommends RustOleum primer spray so this is the product we used in our tests [3].

II. LITERATURE REVIEW

Since the advent of 3D printing as a manufacturing technique is itself recent, in this paper we will take all research conducted on this topic to be considered recent. Therefore, a review of the relevant literature is, in effect, a review of the current state of the industry as it pertains to 3D printing finishing agents, finishing agents themselves representing progress in the field of FDM as concern shifts towards large-scale marketability and aesthetics. Below, we will describe the research that has been put forth on this topic, as well as the areas in which the literature is lacking.

A. Surface Finish

Surface finish is perhaps the most important factor hindering FDM across a wide spectrum of applications. Not only does the characteristic ridged surface impair the aesthetics of the print (making the manufacturing method less well suited for art and design applications and cheapening the perceived quality of prototypes) but the high surface roughness can cause excess friction between parts and poor mold quality in engineering applications. We will proceed to discuss the existing research that pertains to how the three finishing techniques affect surface finish.

1) Epoxy

Currently, there is no research on the effects of epoxy on the surface finish of 3-D printed parts. However, a study performed by Carlos Muzilli et al. in 2013 found that epoxy-coated chromium-cobalt exhibited a surface roughness of less than one micron and showed minimal

cracking after thermocycling. This is evidence that epoxy paint could be an excellent choice for use on 3-D printed parts [4].

2) Acetone

A study performed by Ashu Garg et al. in 2015 studied the effect of cold acetone vapor finishing on the surface finish and dimensional accuracy of 3-D parts printed with P430. The roughness changes are depicted on Fig 1. Surface finish and dimensional accuracy was measured for different types of surface finishes and geometries. A significant decrease in the roughness of the printed parts was observed as shown in the figure below:

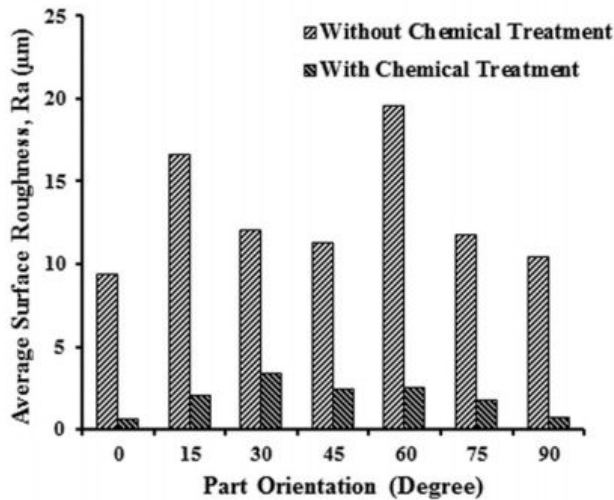


Figure 1: Roughness changes from acetone finishing [5]

However, the dimensional accuracy of the parts was not significantly affected as shown in table 1.

In 2016, Jasgurpreet Chohan et al. expanded this research by developing mathematical models to correlate surface roughness to various treatment parameters such as smoothing time and number of cycles. These models permit the effect on surface

finish to be predicted in advance by systematically adjusting these parameters [6].

Finally, a study performed by L.M. Galantucci et al. demonstrated that acetone-based finishing methods could be used to make 3-D printed parts water-impermeable and biocompatible. This research indicates that acetone vapor finishing could dramatically extend the range of environments in which 3-D printed parts could be applicable [7].

3) Sprays

Currently, there is no research on the effects of primer sprays on the surface finish of 3-D printed parts, as this method is still relatively confined to the hobbyist sector. This is likely due to the nature of sprays, which have difficulty reaching complex internal geometries without specialized tooling and thus have not yet been picked up by industry.

B. Mechanical Properties

While surface finish is the most common criterion against which 3D printing agents are judged, mechanical properties are increasingly important as 3D printing begins to be used not just for prototypes but for final parts that will be used in engineering applications. In this section we included papers that dealt with any sort of mechanical property, and since this topic is still so nascent, there was still a dearth of information. In contrast, in Section III we chose to focus on compression testing the samples to characterize how the different surface treatments affected them mechanically. Below, the scant research on this topic is presented.

1) Epoxy

Currently, there is no research pertaining to the effect of epoxy finishing on the mechanical properties of 3D printed components. However, epoxy is extensively used in projects as a dependable adhesive, and on occasion as a finishing agent, such as in the joining of thin plywood sheets [8]. Due to its reliable joining capabilities, epoxy is predicted by our team to improve the mechanical properties of our specimens. The extent to which the improvement will be is an objective.

TABLE 1.—Results of dimensional accuracy of parts with and without chemical treatment.

Part orientation (degree)	Surface A and Surface B (of triangular groove)							
	From CAD data $b_1 = 30$ mm				From CAD data $b_2 = 13.23$ mm			
	Without chemical treatment		With chemical treatment		Without chemical treatment		With chemical treatment	
	b_1 (mm)	Error (%)	b_1 (mm)	Error (%)	b_2 (mm)	Error (%)	b_2 (mm)	Error (%)
0	30.20	0.67	30.13	0.43	13.05	-1.36	12.95	-2.12
15	30.26	0.87	30.10	0.33	13.33	0.76	13.01	-1.66
30	29.76	-0.80	29.98	-0.07	13.16	-0.53	12.79	-3.33
45	29.91	-0.30	30.03	0.10	13.15	-0.60	12.75	-3.63
60	30.07	0.23	30.11	0.37	13.12	-0.83	12.88	-2.65
75	29.86	-0.47	30.18	0.60	13.03	-1.51	12.99	-1.81
90	29.78	-0.73	30.20	0.67	13.16	-0.53	12.69	-4.08

Table 1: Results of dimensional accuracy of parts [5]

2) Acetone

The most relevant paper on the subject, by L.M.

Galantucci et. al. [7], analyzes the tensile and flexural strength of 3D printed specimens that have been dipped in a mixture of 90% acetone and 10% water, with results shown in the following figures:

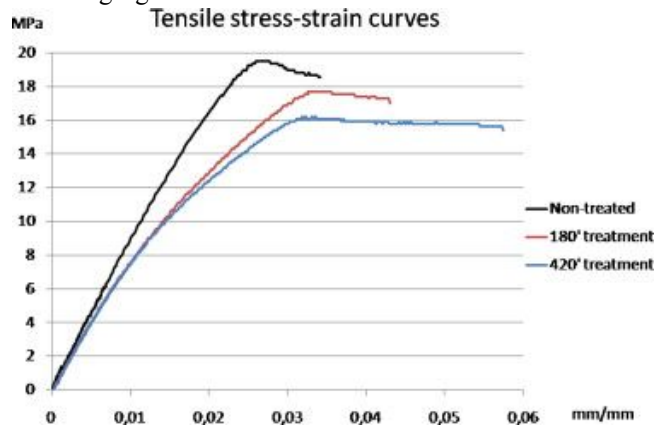


Figure 2: Tensile stress-strain of acetone finished parts [7]

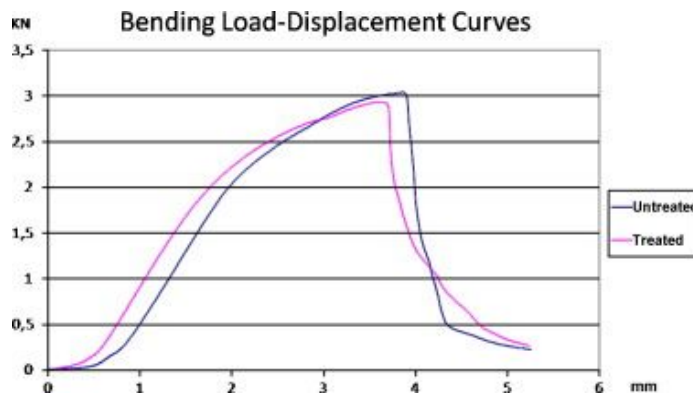


Figure 3: Bending test of Acetone finished parts [7]

This study concluded that the acetone treatment slightly decreased tensile strength, but improved ductility and flexural strength. Interestingly, it also noted that the directionality of the FDM layers became less important to mechanical properties after acetone dipping. This is a common concern in engineering applications of FDM, so this lends acetone great promise as a finishing method as 3D printing gains acceptance outside of prototyping.

3) Sprays

Currently, there is no research on the effects of primer sprays on the mechanical properties of 3-D printed parts. This is also the case for research into the effects of primer on the surface finish. It is suggested again that this lack of interest may be due to the facts that primer sprays have little acceptance within industry as a primary post-processing technique.

The preceding discussion demonstrates that while there exists extensive research into the relationship of cold acetone vapor processing to surface finish quality and mechanical properties, little or no similar research has been performed to understand

the effect of epoxy and primer paint. The experiment that will follow in Section III was designed as a preliminary study in this area and specifically quantifies the effect of these various finishes on the compressive properties and dimensional accuracy of 3-D printed PLA. No serious attempt was made to quantify the effect on surface roughness, although it was possible to make a qualitative comparison.

III. EXPERIMENTATION

A. Design

To start designing the test sample and test itself, the key factor was obtaining access to testing machinery within the 2 week timeframe of this project. Our first choice was to use the 100kN Instron in Hesse Hall, but due to ME108 we were unable to use the machine. Semih Bezci from Professor O'Connell's lab allowed us to use their MTS Mini Bionix 858 with max compression capabilities of 4 kN.

Based on the recommendation of the machine owner, we designed samples to break at 3.8 kN, 95% of the max compressive load. According to MakerBot [9] the compressive strength of PLA reaches its maximum at 13600 PSI so we calculated a suitable cross-sectional area of 40 mm².

Next we designed the sample so it would be radially symmetric and have the cross section of 40 mm². However, the calculated cylinder would have had too high of an aspect ratio to deem safe for testing. So we made a SolidWorks cad model of our sample which is a cylinder: 25.4 mm tall and 10 mm in diameter with 1.5 mm thick walls.

We used Jacobs Hall facilities to print the samples on the TypeA Series Pro 3D printers using PLA filament. We decided to print 3 samples for each of the 3 finishing agents, adding 1 control group of 3, creating 12 samples.

B. Processing and Testing

Samples were subject to a variety of post-processing techniques. This included immersing samples in cold acetone vapor, coating samples with epoxy resin, and painting samples with primer paint.

Cold acetone vapor processing was accomplished by pouring a thin layer of Kleanstrip acetone on the bottom of a small glass container. Samples were glued to the top of an aluminum stand to isolate the samples from the acetone liquid. String was placed around the foil stand so that the samples could be raised and lowered into the glass jar. Samples were immersed for 40 minutes with the lid of the glass jar closed and then removed. An epoxy coating was accomplished by depositing Loctite® 5-Minute Instant Mix™ epoxy on a flat board. The epoxy was spread into a thin layer and then samples were rolled through the thin layer by hand. Samples were left to dry for one hour. Primer painting was accomplished by using a can of RustOleum Automotive 2-in-1 Primer to paint two layers of paint on samples.

After processing, the cross-sectional diameter of all samples were measured with digital calipers. To test, samples were subject to compression testing in order to determine their strength. This was accomplished by using

an MTS Criterion to apply a monotonic compressive load, incremented at 100 N/s, until the samples failed. Pictures were taken of the samples before and after compression testing.

Figure 4: (From left) CAD, Acetone, Spray, Control, Epoxy

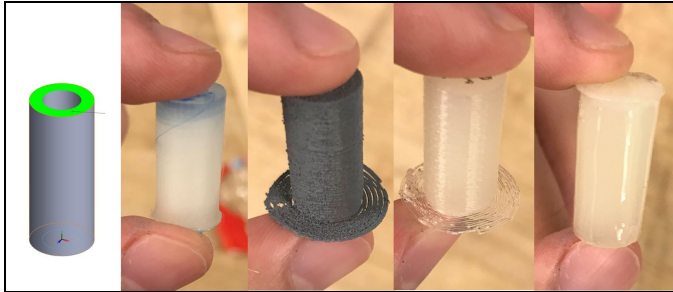
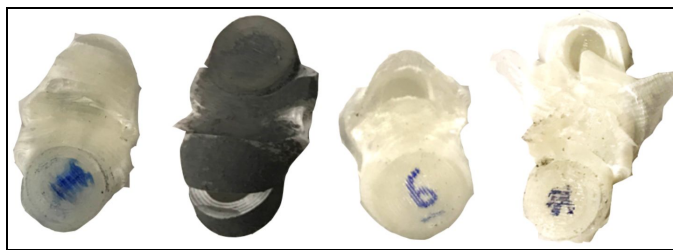


Figure 5: Specimens after compression testing



C. Results

Data acquired through the MTS machine was analyzed using MATLAB. Before comparing the data between the specimens, a MATLAB function cleaned up results by eliminating the data captured after component failure. The cleaned up data was then further processed by averaging the data for the three specimens of each coating. The averaged data is displayed on a stress-strain curve for comparison and mechanical property calculation (Fig. 6).

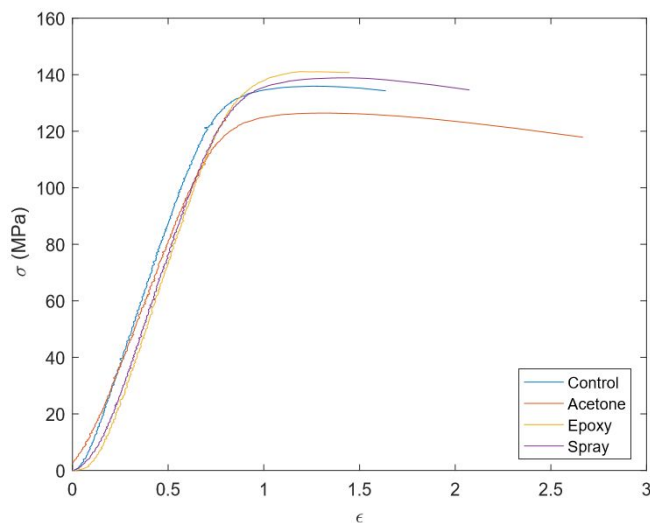


Figure 6: Compression stress-strain curve of specimens

MATLAB functions were used to calculate the Young's

modulus and yield strength in compression for all specimens. The results are displayed in table 2. The mechanical property effect of the coatings are relatively the same with only marginal decrease and increase from the control group.

Finishing Group	Young's Modulus (GPa)	σ_y (MPa)
Control	4.94	-134.00
Acetone	4.35	-127.80
Epoxy	5.07	-140.24
Spray	5.07	-139.05

Table 2: Young's Modulus and yield strength

D. Analysis

The results of the compression testing did not illustrate the predicted performance of the coatings. Our team believed that the spray testing and control would result in the same mechanical properties, since the coating of spray was so thin and is weak to abrasive forces in applications. Furthermore, we believed that the epoxy coating would contribute to a stressed-skin design that would significantly increase the component's mechanical properties. Finally, it was predicted that acetone-treated components would show a slight increase in compressive strength. This would have been consistent with a similar study which found that the compressive strength of acetone-treated ABS samples at a variety of raster angles and immersion times exhibited an average increase in compressive strength of 2-3% [10]. In contrast, acetone-treated samples in this experiment showed a reduction in compressive strength of about 5%. This discrepancy was possibly due to the difference in material, as PLA was used in this experiment instead of ABS. In the literature, the increase in compressive strength was consistent with an increase in the flexural strength as measured in 3-point bending tests. It would be worthwhile to conduct 3-point bending tests on PLA samples to find if the same trend is observed.

It has been suggested that the change in compressive strength might be due to the permeation of the samples by acetone rather than by dissolution. This seems plausible in the case of PLA since it is not strongly soluble in acetone. (In the case of ABS, imaging has revealed that adjacent fibers of printed polymer are, in fact, being bonded together [11].) A useful further investigation would study whether the original compressive strength could be recovered by re-drying the samples.

In regards to the spray and epoxy finishing, our results show very little difference in the effect on mechanical properties between the two methods. The similarity is contradictory to intuition because spray paint is usually very weak to external stresses whereas epoxy is widely known for its strength to stresses. We believe that the similar effect

between the spray and coating may be due to inaccuracy in our experiment due to using only three specimens. Future testing will attempt to prove this hypothesis.

IV. EXPLORING ACETONE

A. Setup

The reason we chose to further explore acetone is that it was the only that show substantial changes in the Young's Modulus and yield strength of around 10% decrease. While we had already examined compressive testing, we wanted to look further into what the acetone was doing to the plastic. So we decided to analyze the effect of acetone treatment on the physical dimensions and mass of samples.

We reprinted new samples and measured the height, diameter and mass before treatment. We treated one set with a 45-minute acetone vapor bath, but found that there was no significant changes in any of three measurements (see Table 3). As a result, we thought that acetone had no effect on the PLA plastic, so we tested another batch of samples by submerging it in acetone for 45 minutes.

B. Results

Below is the result from the first test; there is almost no change in the dimension after 45-minutes of vapor.

Dimension	Before Test (standard error)	After Test (standard error)
Mass (g)	1.52 (.0245)	1.5 (0.0)
Diameter (in)	.4025 (.000822)	.4025 (.000837)
Height (in)	.807 (.000914)	.807 (.000485)

Table 3: Acetone Test 1 (Vapor)

Below is the result from the second test, there is a significant increase in mass of 8.7% and in height.

Dimension	Before Test (standard error)	After Test (standard error)
Mass (g)	1.5 (0.0)	1.63 (0.0211)
Diameter (in)	.403 (.000712)	.4035 (.000898)
Height (in)	.806 (.00147)	.812 (.000494)

Table 4: Acetone Test 2 (Submerged)

There was some interesting physical changes, as the acetone seem to have coated the PLA sample with a white coat that seem to add material to the mass and dimensions.

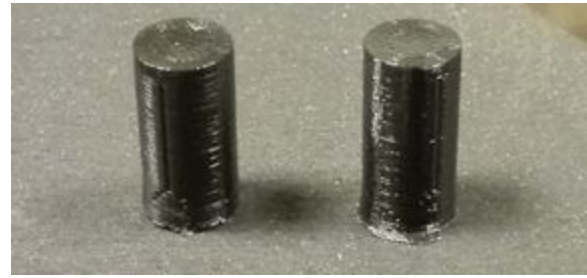


Fig 6: Before Treatment



Fig 7: After Treatment

C. Analysis

We decided to test the effect of Acetone on PLA to see why it made our samples fail at a lower strength. We were testing the hypothesis that the Acetone was taking off material and weakening the sample. However it seem acetone can even add material (if you submerge in it). This calls for more in-depth research on acetone and other finishing agent. Unfortunately we were unable to test more sample on the Instron due to time and machine-access constraints.

B. Future Works

If we have future access to the instron of similar or higher strength, we want to do future testing on spray properties. We would do more in-depth research in acetone because we got very interesting and inconclusive result on why acetone affect the print strength. The end goal is to see how much do each finishing agent affect strength and surface finishing so people can use them as post-printing processes. We also believe that doing beam bending and cantilever bending tests will be more directly related to strength of parts as 3D printed parts generally break and are weaker in those orientation rather than in compression.

V. CONCLUSION

In conclusion, the field of 3-D printing finishing agents is still nascent and more research is urgently needed into how these agents affect prints on a variety of merits. Since surface finish is a major barrier to the spread of FDM as a manufacturing technique in many applications, it is in the interest of everyone involved to characterize the solutions to this problem and understand their potential drawbacks so they can be properly modeled. In pursuit of this, our conclusions showed that epoxy deliver the best surface finish, and future testing is needed to fully characterize the mechanical effects of all types of surface finishing agents. We believe this field is only going to grow in popularity in the coming years, and we hope that the research will proliferate accordingly.

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