Improving Surface Quality of SLA 3D Printed Parts Via Controlled Dip-Coating

by

Shirley Suet-Ning Lu

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

3D printing is useful for rapid prototyping, and is quickly becoming an option to aid in mass manufacturing, whether to make low-volume molds for injection molding and thermoforming or to make unique fixtures. 3D printing via stereolithographic apparatus (SLA) builds parts by curing photopolymer resins layer by layer. SLA 3D printing is often chosen for its relatively high quality surface finish. However, the average surface roughness of SLA 3D printed parts is in the range of 0.4 to 2 μm, which is relatively rough compared to that of polishing/finishing processes, typically 0.1 to 0.4 μm. Therefore, the objective of this research is to determine whether controlled dip-coating can be used to improve surface quality of SLA 3D printed parts.

Contact profilometer data was collected for SLA 3D printed parts that were dip-coated with varying withdrawal speeds (1 mm/s, 5 mm/s, 0.1 mm/s), printed with different resolutions (0.05 mm, 0.1 mm, 0.2 mm), and angled (0, 15, 30, 45, 60, 75 degrees from vertical). The results suggest that dip-coating is an effective means of improving surface quality, achieving 0.3 to 0.5 micron range of surface roughness. However, validating the effect of withdrawal speed and print resolution as well as how print orientation and geometry can be optimized with dip-coating require further study. The results showed that, in general, dip-coating with faster withdrawal speeds tended to give lower surface roughness, and printing at 0.2 mm resolution gave greatest improvement in surface quality, achieving approximately the same surface quality as the dip-coated 0.05 mm resolution parts. Dip-coating appears to increase surface waviness due to the drainage effect of the dip-coating dominating over the layer by layer print periodicity.

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1. Introduction

With the recent innovation in 3D printing, such as greater variety in printing materials and scale of printable objects, this additive manufacturing technique is becoming more popular, not just for prototyping [1]. An alternative to the filament extruding fused deposition modeling (FDM) method of printing, printing via a stereolithography apparatus (SLA) gives higher level of detail and better surface quality. However, SLA printing is still a process that involves printing layer by layer, so the surface quality is limited by the layer height, a disadvantage when compared to the machined and polished finish achieved with traditional subtractive manufacturing.

SLA 3D printing is being explored as a method for aiding manufacturing, specifically in creating molds for injection molding, casting, and thermoforming [2]. Traditionally, injection molds, or dies, are machined out of hardened steel or aluminum, depending on the desired number of uses. Due to the difficulty of machining the hardened metals and the high degree of customization, the cost of these molds ranges from $10,000 to $100,000 – making it cost-effective only when thousands of components are injection molded. 3D printing molds provides a cost-effective alternative for low-run (10-100 parts) production of injection molded parts. However, surface quality is still a limiting factor for specific applications in which the molds are required to have the low surface roughness of a machined finish, such as those for mechanical couplings, high-quality formed parts, microfluidics environments, etc.

To study whether a controlled dip-coating process can improve the surface quality of SLA 3D printed parts, the test part is designed with angles ranging from 0 to 75 degrees (increments of 15 degrees) and dip-coated, varying print resolution and withdrawal speed. The surface roughness was measured with a stylus profilometer to characterize the surface quality of the printed samples in accordance to ISO 4287, specifically studying the average surface roughness R_a and the average surface waviness W_a.

2. Background

2.1 Stereolithographic Apparatus (SLA Printers)

Stereolithography is the process of 3D printing using photopolymer resin and UV light. The liquid photopolymer hardens (cures) after absorbing UV light. Similar to the alternative 3D printing method of filament extrusion, printers that use stereolithography, or stereolithographic apparatuses (SLA), build the part layer by layer. The typical set-up (Figure 1) for a SLA printer involves a build platform that is immersed in a vat of liquid photopolymer. A layer is created when the laser focuses UV light on specific areas of the photopolymer to cure that surface. Once a layer has been created, the platform moves vertically, up or down depending on the model of 3D printer, either lifting the part layer by layer out of the vat of photopolymer or submerging it further [3].

Using stereolithography to 3D print allows for high resolution and accuracy since each layer is fused to the last chemically and the laser is accurately curing select areas. In addition, there is a recoater blade that sweeps across the last layer in the plane of the build platform to both recoat the platform with another layer of resin and cut variations from the surface of the last layer, ensuring uniform thickness [4]. Once a part is finished printing, it is typically cleaned with isopropyl alcohol to remove the excess resin before being post cured by UV exposure [5].

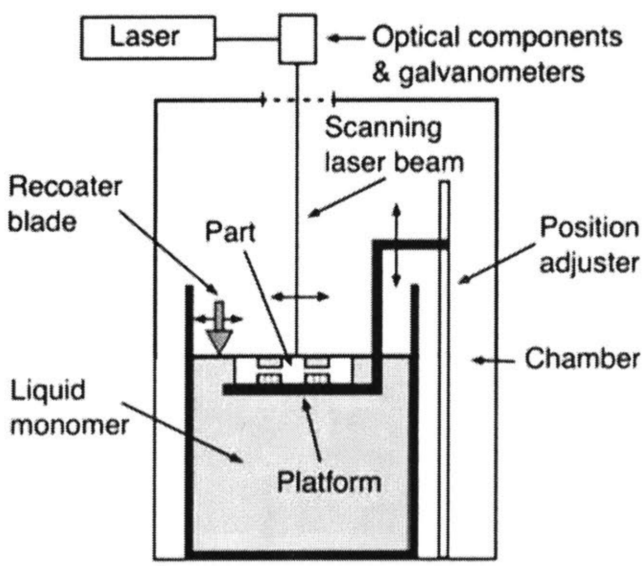

Figure 1: Schematic diagram of a stereolithographic apparatus (SLA printer), with the main components labelled. The test samples were printed with an SLA printer (specifically the Form 1+ printer). [4]

2.2 Dip-coating Process

Dip-coating is typically used to coat an object with a thin-film. Traditionally, the dip-coating process is broken down into three stages: immersion and dwell time, in which the substrate is immersed into the precursor solution at a constant speed and remains immersed for a dwell time to allow "sufficient interaction time…for complete wetting"; deposition and drainage, in which the substrate is withdrawn from the solution at a constant speed, after which excess solution drains from the surface; and evaporation, in which "the solvent evaporates from the fluid, forming the as-deposited thin film" [6].

In this study, the solution used to coat the printed part is Plasti Dip®, an air-dry, specialty rubber coating typically used on cars for cosmetic purposes or tools and other appliances to form a rubberized handle [7]. The product claims attributes such as protection against "moisture, acids, abrasion, corrosion, and skidding/slipping" as well as a functional temperature range of -30°F to 200°F. Plasti Dip® was chosen as the dip-coating solvent for this study because of the ease in which it is applied to the printed part, in particular the process of "curing" the coating is simply allowing it to air-dry for 30 minutes. Since Plasti Dip® is used, the traditional dip-coating process is reduced to the stages of immersion, deposition, and drainage.

2.3 Characterization of Surface Quality

To characterize the effectiveness of dip-coating in recovering surface quality of lower resolution 3D printed parts, the surface roughness is measured with a stylus (contact) profilometer, in accordance to ISO 4287.

2.3.1 Stylus Profilometer

A stylus, or contact, profilometer is commonly used for surface quality measurements. The basic operating principle is that a stylus, typically made of diamond, moves across the surface. The vertical motion of the stylus reflects the surface profile. More specifically, the stylus is attached to a transducer that produces an electrical signal that undergoes analog-to-digital conversion to produce the digital profile stored on the computer for further analysis [8]. This operating principle is depicted in the following figure.

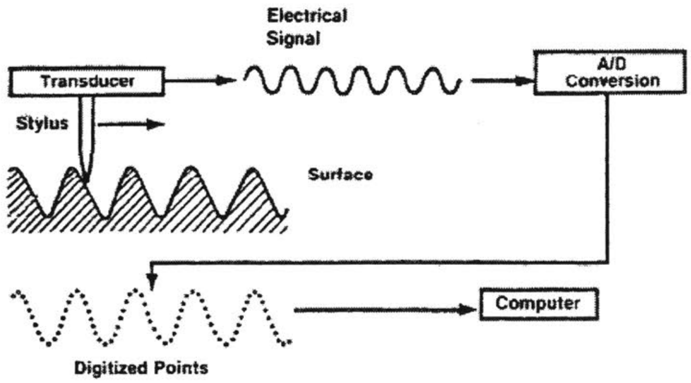

Figure 2: Schematic diagram of a stylus (or contact) profilometer, with the relevant components labelled. The test samples were measured with a stylus profilometer (specifically the Bruker DXT-A Stylus Profilometer). [8]

2.3.2 Surface Characteristics of Interest

The surface texture or quality is typically characterized by two main parameters: surface roughness and waviness. As shown in the following figure, surface roughness refers to "closely spaced irregularities ([ex.] cutting tool marks, grit of grinding wheel" whereas surface waviness refers to "more widely spaced irregularities ([ex. from] vibration and chatter)" [8].

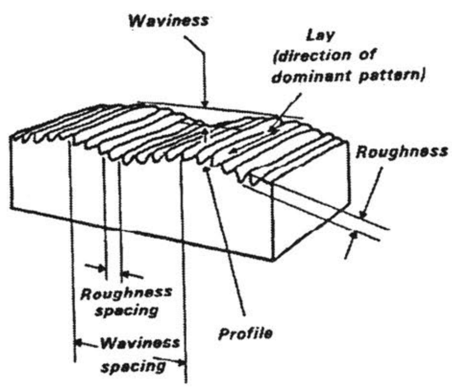

Figure 3: Diagram depicting surface characteristics, where roughness is the "closely spaced irregularities ([ex.] cutting tool marks, grit of grinding wheel" and waviness is the "more widely spaced irregularities ([ex. from] vibration and chatter)" [8]

The characteristic parameters of interest in this study are R_a, average roughness, and W_a, average waviness. According to ISO 4287, R_a is defined as "the arithmetical mean of the absolute values of the profile deviations [in height] from the mean line of the roughness profile" [9]. Similarly, W_a is the average of absolute values of deviations from the mean line of the waviness profile. It is important to note that R_a and W_a are not intrinsic to the material or forming process. These two parameters generally increase as the sampling length increases [8].

R_a is a common and useful parameter used to characterize surface quality, in particular in automotive and other metalworking industries – though it is important to note that average roughness alone does not fully characterize a surface [8]. W_a is included in this study since the 3D printing process has intrinsic periodicity due to printing layer by layer.

3. Experimental Design

3.1 Percent Improvement in Surface Quality

The test part is designed with angles ranging from 0 to 75 degrees (increments of 15 degrees) and dip-coated, varying print resolution and withdrawal speed. In order to quantify the effect of dip-coating on the surface quality, the percent improvement is defined by the following equation:

$$\%\ improvement\ in\ x = \frac{-(x_{dipped} - x_{baseline})}{x_{baseline}} \times 100\%$$

Where x is R_a or W_a, and baseline refers to test parts that are not dipped or post-processed in any way after printing.

The sign convention is such that the percent improvement in a certain parameter is positive when the surface quality is improved. This percent improvement is calculated as a function of print resolution and withdrawal speed independently via two separate experiments.

To compare percent improvement as a function of print resolution, test parts are printed and dipped at a constant 1 mm/s withdrawal speed with three different print resolutions: 0.05 mm, 0.1 mm, and 0.2 mm. To compare percent improvement as a function of withdrawal speed, a dip-coating process parameter, test parts are printed at a constant print resolution of 0.1 mm and then dipped with three different withdrawal speeds: 0.1 mm/s, 1 mm/s (instructed use of Plasti Dip®), and 5 mm/s.

3.2 Preparing SLA 3D Printed Test Samples

The test samples (shown in Fig. 4) are SLA 3D printed using the Form 1+, Formlabs' desktop printer. The photopolymer used is the Standard Clear Resin (FLGPCL02) from Formlabs. The test parts are arranged and oriented on the build platform near the hinge so that they were less likely to shear off in the printing process.

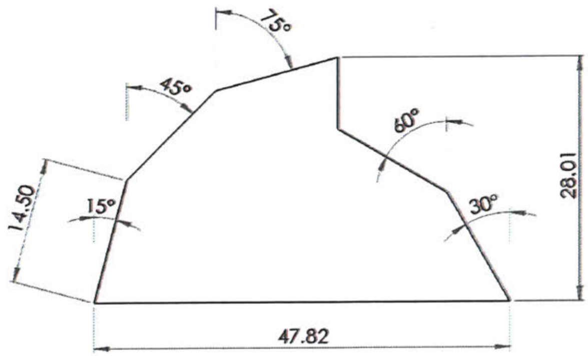

Figure 4: Relevant dimensions (units in millimeters) of the test sample labeled; thickness into the page is 10 mm. Samples are 3D printed using a desktop SLA printer. This test part has angled features, measured from the vertical, ranging from 0 degrees (front face of part – not labeled) to 75 degrees. Each angled face has the same length of 14.50 mm.

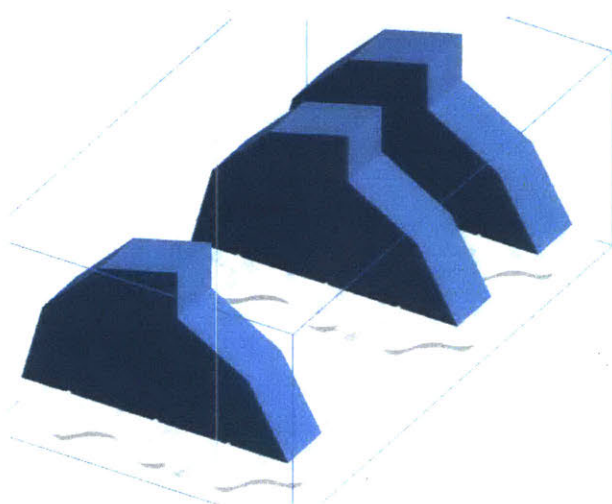

Figure 5: Test parts oriented on the Form 1+ (desktop SLA 3D printer) build platform. In this screenshot of the build platform software, the test parts are in blue while the supports are white. The test parts are printed in clear resin, and its dimensions are given in Figure 4. Because the parts were relatively small, they were placed near the hinge on the print platform and oriented as shown to prevent them from shearing off in the printing process.

After the test parts were printed, the parts, still on the print platform, are post-cured for 30 minutes in the UV oven (Dymax Light Curing System – Model 2000 Flood). This ensures that the parts are dry for better adhesion of the Plasti Dip®. For this post-curing step, the area of the print platform that does not hold the parts was covered in aluminum foil to prevent the curing the excess resin on the platform (Figure 6).

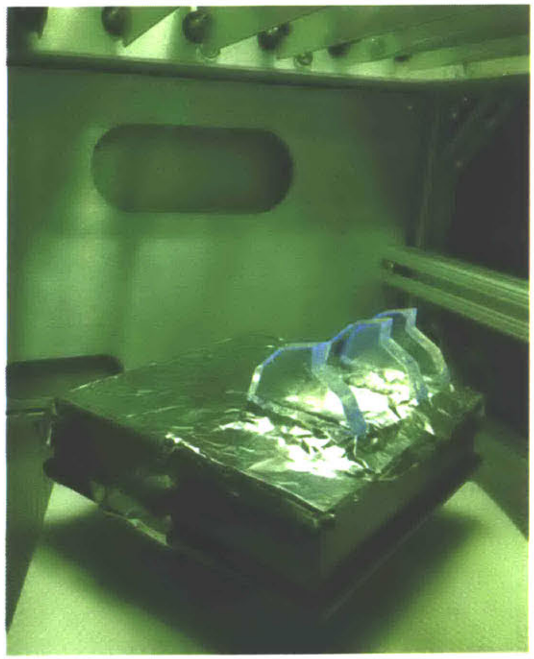

Figure 6: Test parts curing in the UV oven so that the surface is completely dry for better adhesion in dip-coating with Plasti Dip®. The platform is covered in aluminum foil to prevent the curing of excess resin residue from the printing process.

Once the parts are dry, the dip-coating process is performed. Using the Form 1+ OpenFL Python API, the dip-coating process can be done immediately following the completion of the printing using the printer itself before the removal of the printed parts from the platform. The dip-coating code, available in Appendix A, uses the printer's stepper motor to immerse the part into the container of dip-coating solvent and to withdraw at a specified velocity. A container of Plasti Dip® is placed on top of the tank, resting on a piece of aluminum sheet metal, as shown in the following figure.

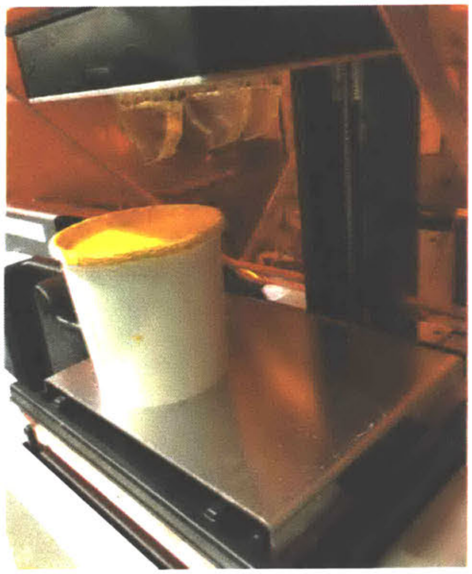

Figure 7: Dip-coating set-up. An aluminum sheet is fitted to the top of the resin tank of the Form 1+ printer so that the dip-coating container of Plasti Dip® can sit securely.

The parts are then allowed to air-dry for a minimum of 30 minutes as recommended by the instructions for Plasti Dip®. Once the parts are dry, the test part is freed from its supports, and the print platform is cleaned. Because of the supports, the test parts at this stage have an uneven bottom surface, so the bottom surface is then sanded with a sanding disk. The steps to prepare the test samples for this study are summarized in the following diagram (Figure 8).

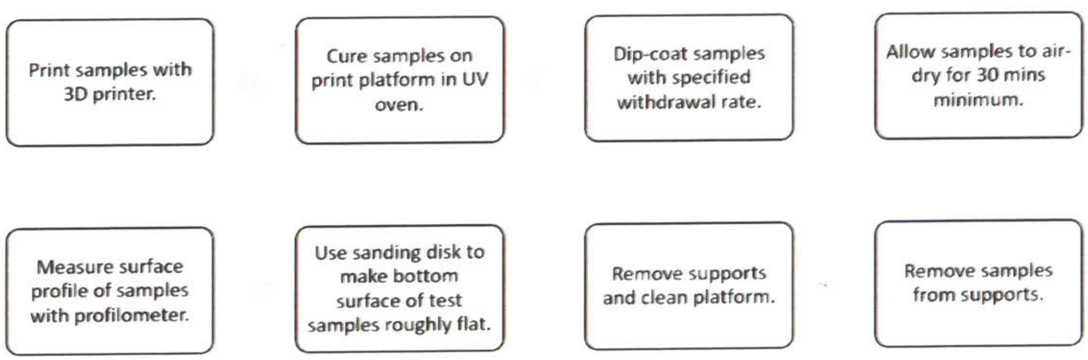

Figure 8: Summary of experimental procedure of preparing test samples for this study.

3.3 Surface Roughness Measurements

To obtain the surface roughness parameters outlined in Section 2.3 Characterization of Surface Quality, a stylus, or contact, profilometer (Bruker DXT-A Stylus Profilometer) is used. In accordance to ISO 4287, a 45 degree stylus with a 2-μm radius tip is used with 1.75 mg of tip force applied. By starting at the calibration tip force of 2 mg, this tip force of 1.75 mg is determined via trial and error to prevent scratching the surface. As outlined in the standard, the scan length, or evaluation length, of the measurements is nominally 12500 μm (i.e. 12.5 mm) with five sampling lengths for parameter calculation.

In order for the angled surfaces to be measured with the stylus profilometer, an angle guide is 3D-printed for the part to sit on so that the surface of interest is effectively horizontal. This angle correction can be seen in the following figure. The details of the design and fabrication of the angle guide may be found in Appendix C.

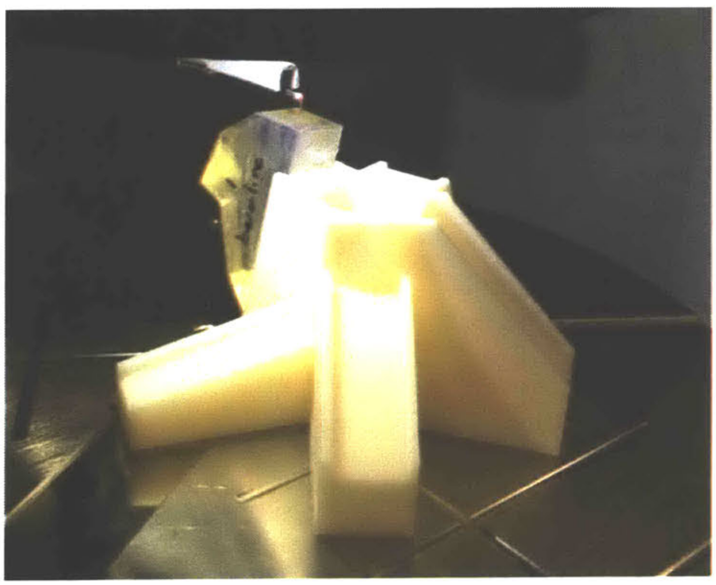

Figure 9: Profilometer measurement set-up. A 3D-printed angle guide is used in the data collection process to make each angled surface of interest effectively horizontal to accommodate the stylus profilometer.

Even with the angle guide, due to the angled nature of the part and roughly flattened bottom surface, the range of the hills and valleys had to be set at 524 μm to prevent the measurements from saturating. This range provides a vertical resolution of 0.008 μm [10]. With the scan length of 12500 μm, the surface characteristics are calculated with five sampling lengths as described in ASTM D7127 – 17 Measurement of Surface Roughness of Abrasive Blast Cleaned Metal Surfaces Using a Portable Stylus Instrument [11]. Before calculating roughness parameters, the data is first leveled using the Bruker software's built-in data leveling scheme – "Linear & Curvature Removal."

In addition to the quantitative profilometer data, a digital microscope (Zeiss Smartzoom 5) is used to image the surface texture of the dip-coated parts and the baseline/non-coated parts for qualitative comparison.

4. Results and Discussion

4.1 Effect of Test Part Design and Dip-coating Solvent

In analyzing the profilometer results, it is important to consider the test part design and choice of dip-coating solvent and how this skews the results. In particular, the 75 degree face of the test part is the lowest point of the test part when it is in the printing/dipping orientation, as seen in Figure 7. As a result, there is a visible "bulge" on some of the test parts on the 75 degree face (Figure 10) as this is where drainage occurs, dramatically increasing the calculated waviness.

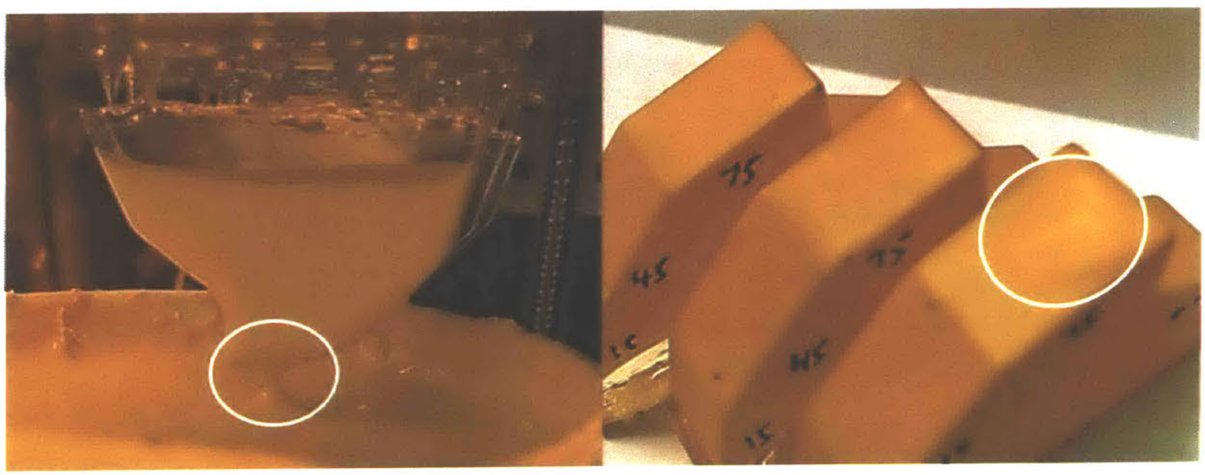

Figure 10: "Bulge" on 75 degree face of test part (indicated on right) due to being the lowest point in the print/dip orientation (indicated on left).

Due to the 15 degree and 30 degree face being the highest point of the test part when it is in the printing/dipping orientation, those faces on some of the test parts are not fully dipped/covered with the Plasti Dip®. The data collected for these faces still had a nominal scan length of 12500 μm. However, the range for calculating the R_a and W_a is manually adjusted to exclude regions that are not dipped. This results in an effective scan length of roughly 10000 μm (on average). This is important to consider since the R_a and W_a typically increase with scan length.

The effect of this drainage pattern causing significant waviness can likely be mitigated with the use of a less viscous fluid as the dip-coating solvent. The surface tension of the less viscous fluid will be lower, allowing that "release" that causes the "bulge" to occur without pulling too much of the fluid away from the part. However, the use of a different dip-coating solvent to mitigate waviness may result in adverse effects on the surface roughness since the decreased surface tension may decrease the ability of the solvent to adhere well to the surface to be dip-coated.

4.2 Effect of Dip-coating Withdrawal Speed

An important parameter of the dip-coating process is withdrawal speed of the part from the dip-coating solvent. The general effect of the withdrawal speed is that the faster the speed, the more solvent is coated on the part because there is less time for the fluid to drain from the part. To study the effect of withdrawal speed on R_a and W_a, the withdrawal speed was varied at 1 mm/s (recommended by the Plasti Dip® manufacturer), 5 mm/s, and 0.1 mm/s. The parts tested were printed at a fixed print resolution of 0.1 mm. The following table presents the averaged roughness and waviness parameters obtained from this experiment, with uncertainties proportional to the standard deviation of the 5 measurements per sample.

Table 1: Averaged roughness R_a and waviness W_a surface parameters calculated from profilometer data (nominal scan length of 12500 μm) for samples printed at 0.1 mm print resolution and varying dip-coat withdrawal speeds.

Withdrawal Speed [mm/s]	Angle From Vertical [deg]	R_a [μm]	W_a [μm]
baseline	0	0.45 ± 0.19	16.2 ± 8.24
baseline	15	0.86 ± 0.30	6.24 ± 3.11
baseline	30	0.57 ± 0.19	6.43 ± 3.02
baseline	45	0.64 ± 0.12	8.01 ± 3.45
baseline	60	0.49 ± 0.10	10.49 ± 4.54
baseline	75	0.36 ± 0.02	11.48 ± 1.38
1	0	0.37 ± 0.01	4.53 ± 1.89
1	15	0.37 ± 0.04	9.92 ± 3.23
1	30	0.38 ± 0.04	12.06 ± 3.08
1	45	0.39 ± 0.01	4.16 ± 0.66
1	60	0.39 ± 0.01	4.16 ± 2.84
1	75	0.34 ± 0.03	20.20 ± 4.66
5	0	0.42 ± 0.04	5.81 ± 1.41
5	15	0.39 ± 0.04	3.38 ± 0.63
5	30	0.38 ± 0.02	7.62 ± 1.96
5	45	0.38 ± 0.03	4.50 ± 1.63
5	60	0.38 ± 0.02	17.59 ± 5.38
5	75	0.33 ± 0.01	21.34 ± 6.03
0.1	0	0.53 ± 0.02	6.53 ± 1.39
0.1	15	0.53 ± 0.11	17.11 ± 3.36
0.1	30	0.49 ± 0.03	10.40 ± 5.55
0.1	45	0.58 ± 0.04	12.66 ± 2.65
0.1	60	0.50 ± 0.03	13.72 ± 9.12
0.1	75	0.48 ± 0.06	10.02 ± 3.51

The following table shows the comparison of the data to the baseline 0.1 mm data set for purposes of determining whether the dip-coated data and the baseline data for each set of parameters are statistically significantly distinguishable. The results of the student t-test show that 24 out of 36 data sets gave statistically significant results, defined as at least 90% confident for the purposes of this study.

Table 2: Student t-test performed on the baseline data set (0.1 mm print resolution) and the dip-coated data set with constant 0.1 mm print resolution and varying withdrawal speed. Percent confidence that the two data sets are statistically significantly distinguishable are reported for both R_a and W_a.

Withdrawal Speed [mm/s]	Angle From Vertical [deg]	R_a Confidence [%]	W_a Confidence [%]
1	0	63.31	98.00
1	15	98.76	93.19
1	30	94.44	98.99
1	45	99.88	89.54
1	60	94.25	96.41
1	75	73.74	99.33
5	0	24.73	96.97
5	15	98.57	92.33
5	30	94.01	57.48
5	45	99.67	94.17
5	60	95.40	96.73
5	75	95.46	98.79
0.1	0	65.80	96.21
0.1	15	95.77	99.97
0.1	30	69.81	84.42
0.1	45	74.64	97.35
0.1	60	35.48	55.28
0.1	75	99.56	63.72

Based on Table 2, for only the statistically significant data sets, the percent improvement was calculated as explained in Section 3.1 Percent Improvement in Surface Quality and plotted in Figure 11, along with propagated uncertainty.

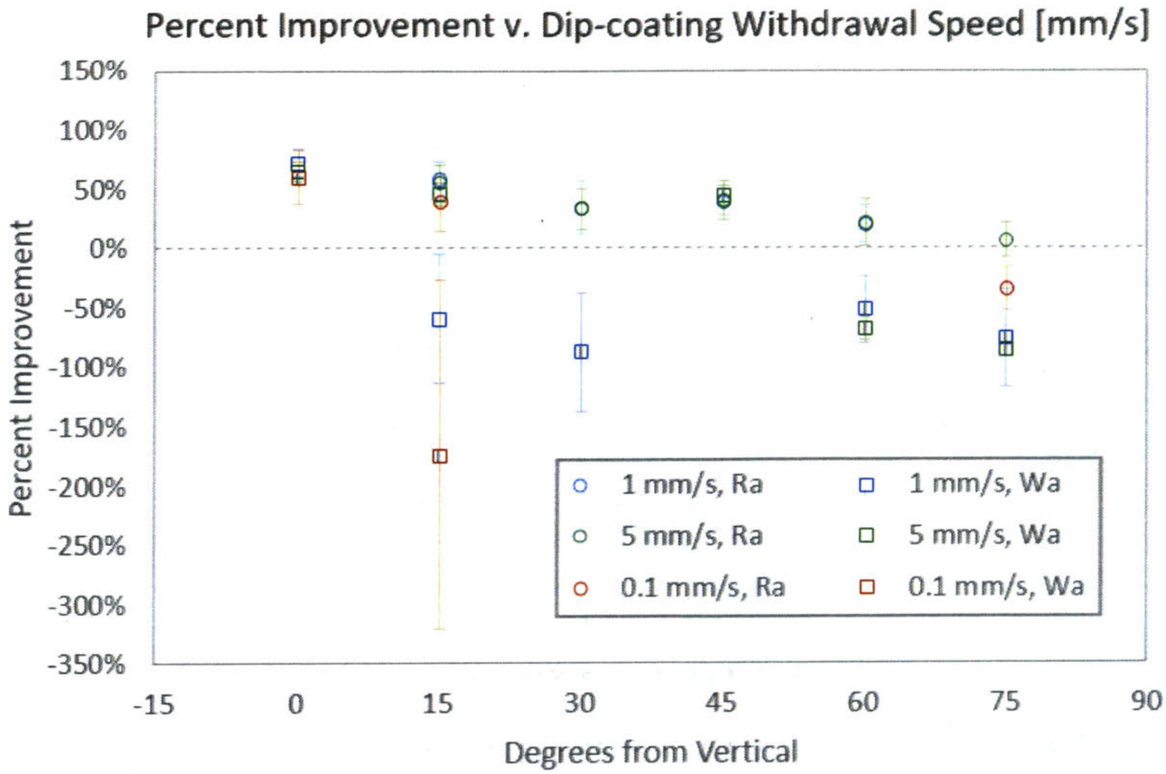

Figure 11: Percent improvement of surface quality parameters, R_a and W_a, for each degree face and varying dip-coating withdrawal speeds: 1 mm/s, 5 mm/s, 0.1 mm/s.

The withdrawal speed that is most consistent of the three to show positive percent improvement is 5 mm/s. This correlates with the increased thickness of the free layer (shown in the diagram reproduced below, Figure 12) when withdrawal speed increases, detailed in a related study by Seiwert, Clanet, and Quéré – "Coating of a textured solid" [12].

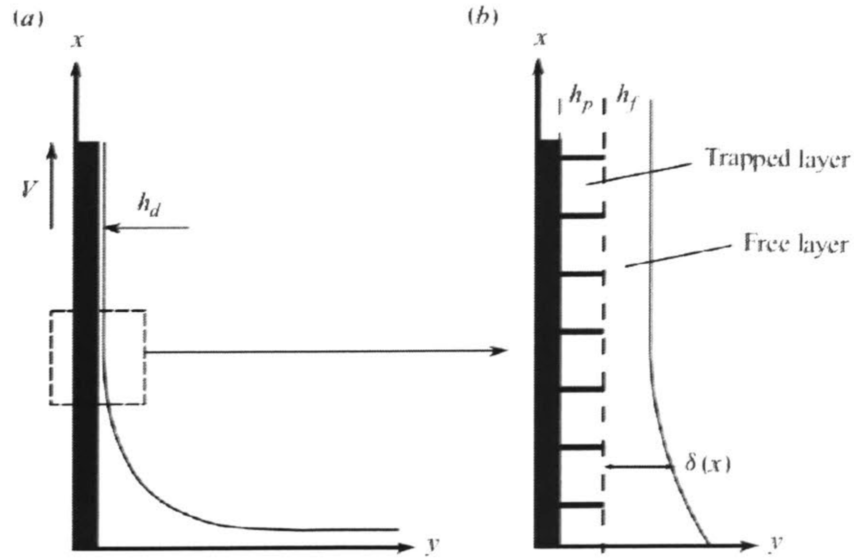

Figure 12: Free layer and trapped layer of fluid when a textured vertical plate is withdrawn from a fluid bath. The free layer thickness increases as withdrawal speed increases. Diagram reproduced from "Coating of a textured solid" by Seiwert, Clanet, and Quéré.

The test part used in this study is effectively a textured solid since the printed surface has periodic "bumps" that result from the 3D printing process, corresponding to the pillars that entrain the trapped layer as described by Seiwert. The fastest withdrawal speed, 5 mm/s, showed the most consistent positive percent improvement because it resulted in the thickest free layer formation. As a result, the surface measured is the free layer surface, whose roughness is independent of the original roughness caused by 3D printing. Therefore, the greater the withdrawal speed, the better the surface quality (less rough). However, there is a tradeoff with feature resolution; as withdrawal speed increases, the free layer will get thicker and may no longer pick up small features on the part's surface. The data for samples withdrawn at 1 mm/s reflects a similar trend to that of 5 mm/s, with positive percent improvement in R_a for all degree faces. However, in terms of waviness, as expected, the samples withdraw at 5 mm/s has lower waviness W_a.

On the other hand, the samples dip-coated with 0.1 mm/s withdrawal speed show the worst percent improvement overall, with negative improvement for the majority of the angles (as seen in Table 1). It is important to note that only 5 of the 12 data sets with 0.1 mm/s withdrawal speed group are statistically significantly different from the baseline (not dip-coated) samples. Therefore, the negative percent improvement implies that with a slow withdrawal speed of 0.1 mm/s, not only is there poor feature resolution in following the printed layer periodicity, the surface has become rougher as a result of the dip-coating.

4.3 Effect of Print Resolution

Another parameter considered in this study is the print resolution, or layer height, a parameter of the 3D printing process. The effect of this parameter on the dip-coated surface is important to consider as print resolution contributes significantly to part preparation time. In general, according to Formlabs, "printing at 25 microns vs. 100 usually increases the print time four-fold" [13]. In this study, to print one test part at: 0.2 mm, 39 mins; 0.1 mm, 1 hour 5 mins; for 0.05 mm, 2 hours 6 mins. To study whether there is an optimal combination of print resolution and dip-coating to decrease part fabrication time, samples are printed at three different resolutions (0.1 mm, 0.2 mm, 0.05 mm) and dip-coated with a fixed withdrawal speed of 1 mm/s (recommended by the Plasti Dip® manufacturer). The following table presents the averaged roughness and waviness parameters obtained from this experiment, with uncertainties proportional to the standard deviation of the 5 measurements per sample.

Table 3: Averaged roughness R_a and waviness W_a surface parameters calculated from profilometer data (nominal scan length of 12500 μm) for samples with fixed dip-coat withdrawal speed of 1 mm/s and varying 3D print resolutions: 0.2 mm, and 0.05 mm. Note that the data for 0.1 mm print resolution may be found in Table 1.

0.2 mm Print Resolution			
Sample Type	Angle From Vertical [deg]	R_a [μm]	W_a [μm]
baseline	0	1.10 ± 0.06	8.29 ± 3.43
baseline	15	1.08 ± 0.05	8.89 ± 1.87
baseline	30	1.83 ± 0.06	23.49 ± 4.00
baseline	45	1.85 ± 0.19	23.37 ± 2.18
baseline	60	1.22 ± 0.28	29.87 ± 3.26
baseline	75	0.65 ± 0.28	38.28 ± 9.48
dip-coated	0	0.43 ± 0.02	10.18 ± 1.31
dip-coated	15	0.45 ± 0.03	16.04 ± 4.00
dip-coated	30	0.44 ± 0.03	14.87 ± 1.40
dip-coated	45	0.43 ± 0.05	9.69 ± 0.79
dip-coated	60	0.47 ± 0.02	13.22 ± 5.62
dip-coated	75	0.42 ± 0.10	23.83 ± 16.01
0.05 mm Print Resolution			
Sample Type	Angle From Vertical [deg]	R_a [μm]	W_a [μm]
baseline	0	1.08 ± 0.11	6.83 ± 1.42
baseline	15	1.79 ± 0.32	22.63 ± 1.10
baseline	30	1.02 ± 0.40	9.71 ± 0.88
baseline	45	1.35 ± 0.36	12.37 ± 1.58
baseline	60	0.61 ± 0.05	6.03 ± 1.51
baseline	75	0.47 ± 0.08	6.26 ± 0.93
dip-coated	0	0.43 ± 0.03	5.04 ± 1.03
dip-coated	15	0.44 ± 0.02	10.03 ± 1.55
dip-coated	30	0.42 ± 0.02	11.22 ± 6.38
dip-coated	45	0.41 ± 0.03	8.29 ± 2.24
dip-coated	60	0.48 ± 0.03	13.70 ± 3.43
dip-coated	75	0.45 ± 0.04	20.67 ± 7.23

As described in the previous section (Section 4.2 Effect of Dip-coating Withdrawal Speed), the data is similarly compared to the baseline data set for each print resolution to determine whether the dip-coated data and the baseline data are statistically significantly distinguishable, in other words, whether dip-coating is effective. The results of the student t-test show that 30 out of the 36 data sets gave statistically significant results, defined as at least 90% confident for the purposes of this study.

Table 4: Student t-test performed on the baseline data set for each print resolution and the dip-coated data set with the corresponding print resolution and constant withdrawal speed of 1 mm/s. Percent confidence that the two data sets are statistically significantly distinguishable are reported for both R_a and W_a.

Print Resolution [mm]	Angle From Vertical [deg]	R_a Confidence [%]	W_a Confidence [%]
0.1	0	63.31	98.00
0.1	15	98.76	93.19
0.1	30	94.44	98.99
0.1	45	99.88	89.54
0.1	60	94.25	96.41
0.1	75	73.74	99.33
0.2	0	100.00	75.78
0.2	15	100.00	99.33
0.2	30	99.94	99.65
0.2	45	100.00	100.00
0.2	60	99.78	99.96
0.2	75	90.15	91.08
0.05	0	99.99	96.73
0.05	15	99.96	100.00
0.05	30	99.54	42.16
0.05	45	99.76	99.39
0.05	60	99.98	99.75
0.05	75	36.33	99.35

Based on Table 4, for only the statistically significant data sets, the percent improvement was calculated as explained in Section 3.1 Percent Improvement in Surface Quality and plotted in Figure 13, along with propagated uncertainty.

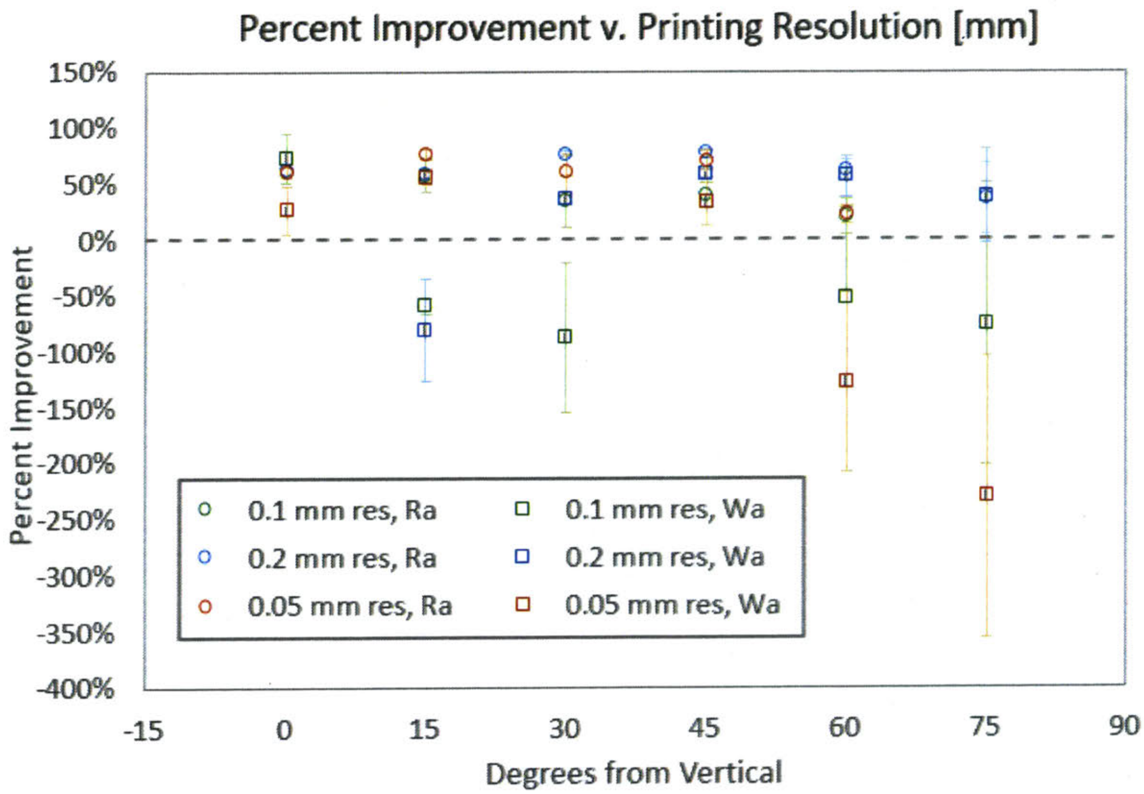

Figure 13: Percent improvement of surface quality parameters, R_a and W_a, for each degree face and varying print resolutions: 0.1 mm, 0.2 mm, and 0.05 mm.

The print resolution that most consistently shows positive percent improvement in surface quality parameters when dip-coated is 0.2 mm while the data for test parts printed at 0.1 mm resolution were most statistically insignificant, i.e. indistinguishable from its baseline. This suggests that there is no clear relationship between print resolution and dip-coating effectiveness since the general trend, in order of greatest overall improvement, is 0.2 mm, 0.05 mm, 0.1 mm. Similar to the results found in studying the effect of withdrawal speed, there does not appear to be a clear trend in the improvement, or lack thereof, of the surface waviness W_a parameter.

In terms of application, this experiment shows that printing at 0.2 mm print resolution, which would give the fastest print time, is actually most effective in recovering the surface quality via controlled dip-coating. As seen in the data in Table 3, in addition to having the greatest percent improvement overall, the actual roughness and waviness values achieved for 0.2 mm print resolution are very similar to those of the other print resolutions – in the range of 0.4 to 0.5 μm compared to a baseline of 1 to 2 μm. Placing this in the context of other forming processes

(Appendix B), the baseline roughness for 0.2 mm print resolution is roughly comparable to "metal cutting" (turning, milling, reaming, etc.) whereas the dip-coated roughness for 0.2 mm print resolution is comparable to "abrasive" processes (ex. grinding, barrel finishing, electro-polishing, etc.) [14].

For a qualitative comparison of the test parts with different print resolutions, digital microscope images are taken of the 45 degree face of the baseline test parts and the corresponding dip-coated test parts that were dip-coated with a withdrawal speed of 1 mm/s. The 45 degree face is chosen for its consistency as it was not impacted significantly by the part design in regards to drainage or lack of total dip-coating. The images are shown on the following page (Figure 14). All images are taken at the same magnification on the Zeiss Smartzoom 5. The print layers are distinctly seen in the baseline resolution images on the left while it can be seen that the appearances of the surface after dip-coating (on the right) are very similar, regardless of print resolution. Note that all the microscope images were taken at the same magnification (300x). This corresponds to the data which shows that the surface roughness after dip-coating was in the range of 0.34 to 0.48 for all print resolutions dip-coated with a withdrawal speed of 1 mm/s.

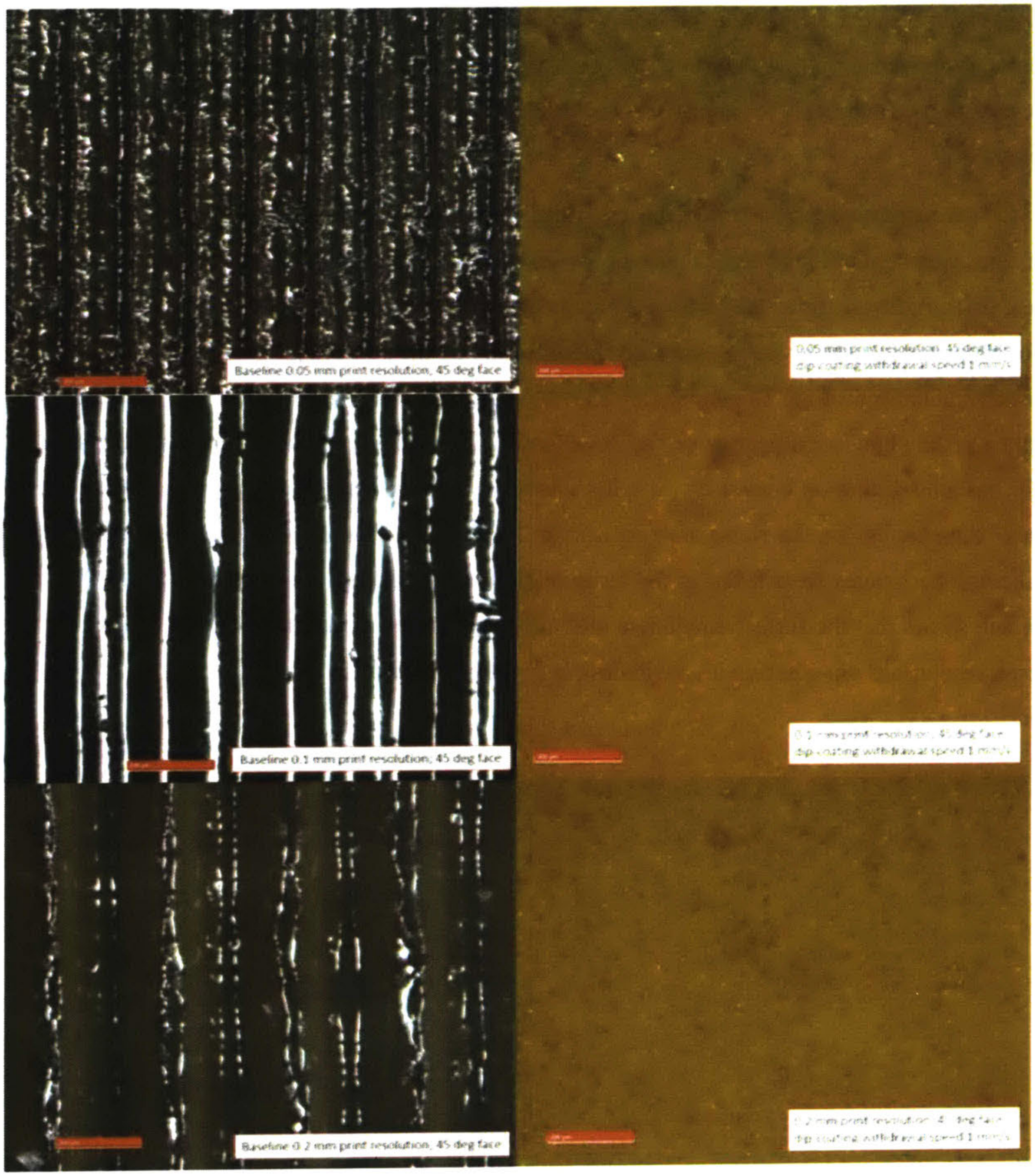

Figure 14: Digital microscope (Zeiss Smartzoom 5) images to qualitatively compare surface quality of parts with different print resolutions (0.05 mm, 0.1 mm, 0.2 mm) - with and without dip-coating (withdrawal speed of 1 mm/s). The red scale bar in each image corresponds to 200 μm. Qualitatively, the appearance of the dip-coated samples are very similar, regardless of the print resolution.

4.4 Effect of Geometry

The test part is designed with faces of different angles from the vertical. This is intended to observe whether the angle affected the surface roughness significantly, and hence, whether print orientation can be optimized to improve surface quality overall or to target a surface to obtain a good surface quality on that desired surface via dip-coating. With the ultimate goal of relating any geometry to dip-coating effectiveness, this study began by looking at angles due to the related work detailed in "Angle-dependent dip-coating technique (ADDC) an improved method for the production of optical filters" by Eberle and Reich [15]. This work explains how individual layer thickness can be controlled via dip-coating parameters such as withdrawal speed (or lifting speed) and angle of inclination.

To study the effect of the angled geometry specifically, each test part has faces at six different angles: 0, 15, 30, 45, 60, and 75 degrees – measured from the vertical. Based on the data presented in earlier sections, the 0 degree and 45 degree faces appear to show consistent positive improvement regardless of the varying sets of parameters. As explained in Section 4.1 Effect of Test Part Design and Dip-coating Solvent, the data pertaining to the 15 degree, 30 degree and 75 degree faces have the most propagated uncertainty as seen in the following plot. In general, it appears the average surface roughness R_a has a positive percent improvement while W_a depends much more on the angle.

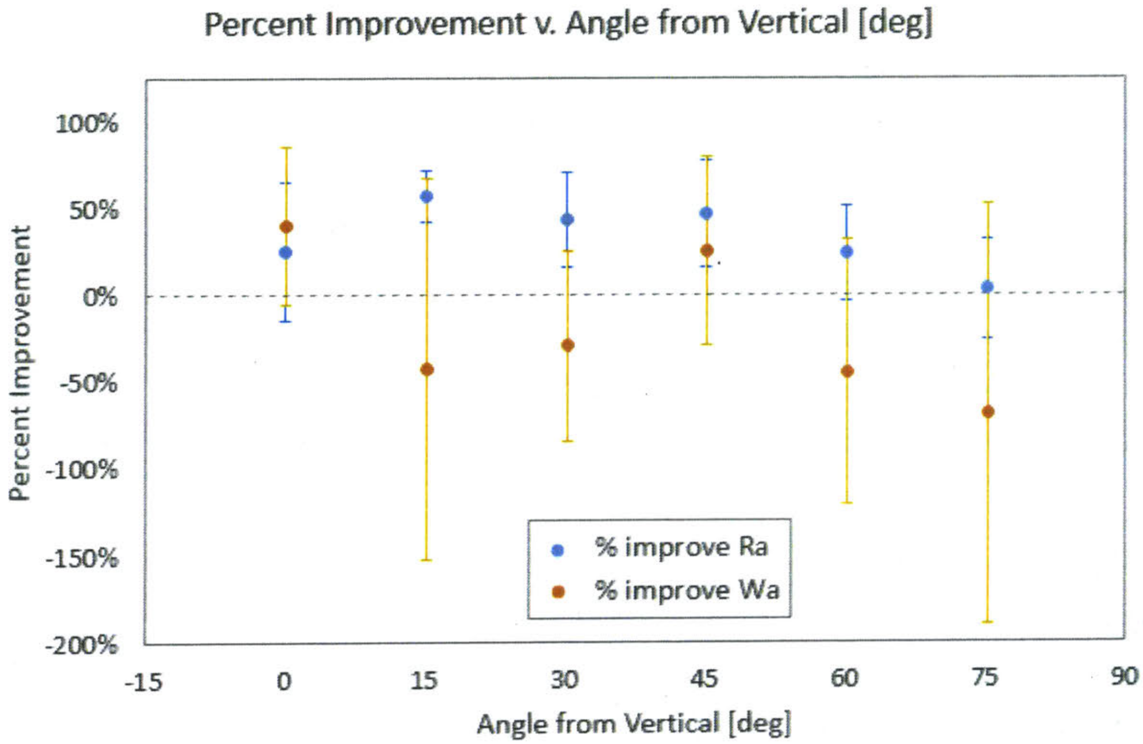

Figure 15: Averaged percent improvement of surface quality parameters, R_a and W_a, for each degree face aggregated from all data sets with varying parameters.

5. Conclusions

In general, controlled dip-coating of a 3D printed test part will change its surface quality: decreasing average surface roughness R_a but increasing average surface waviness W_a. With controlled withdrawal of the part from the bath of solvent (Plasti Dip®), the resulting surface has a more uniform profile since the small irregularities are covered with the dip-coated layer, hence the improved surface roughness. The average surface waviness likely increased as a result of the test part geometry, which influenced the way the dip-coated solvent drained. The resulting bumps were much larger than the print layers, significantly increasing the surface's waviness. This can be seen more clearly in the following plot visualization of the effectiveness of dip-coating. The data points are the averaged surface parameters for each subset of experiments (varying print resolution, withdrawal speed, and angles).

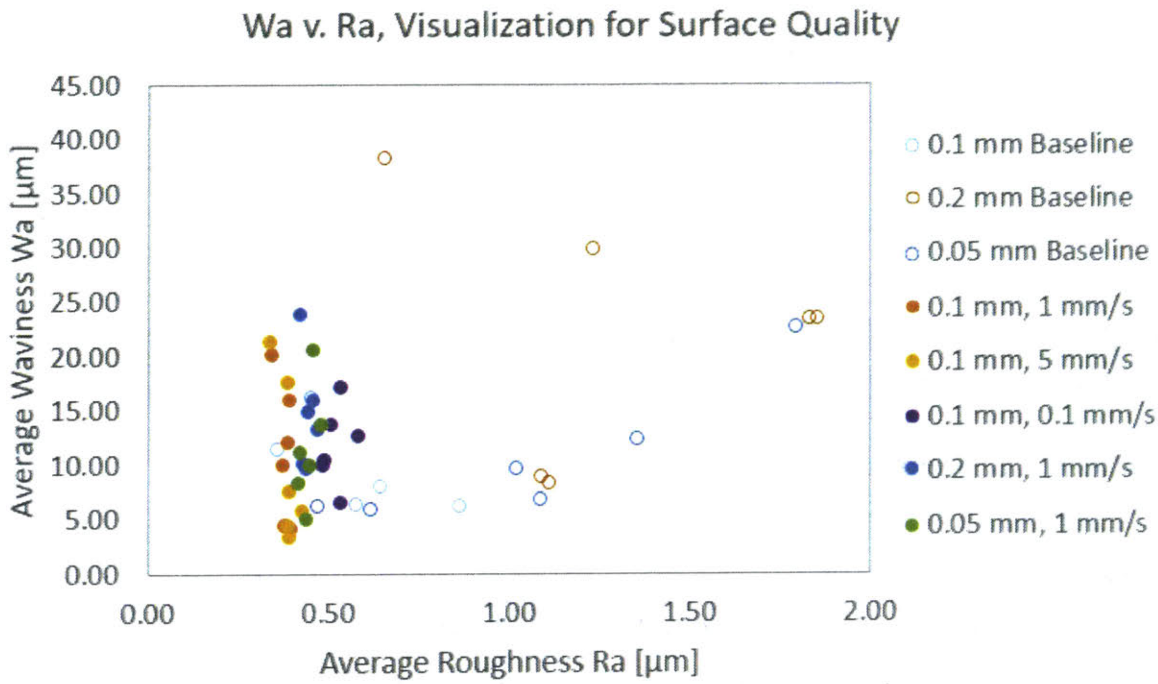

Figure 16: Plot of average surface waviness W_a v. average surface roughness R_a for dip-coating effectiveness visualization. Dip-coating appears to be effective in reducing average surface roughness, but not average surface waviness.

The R_a of the SLA 3D printed parts in this study without dip-coating were in the range of 0.5 to 1.8 µm and with dip-coating, in the range of 0.3 to 0.5 µm. Relative to other manufacturing processes, these surface roughness values are comparable to milling/turning and abrasive finishing (ex. grinding, electro-polishing, etc.), respectively.

Based on the varying experiments in this study, the most effective combination of withdrawal speed and print resolution appears to be printing with 0.2 mm print resolution (or layer height) and dip-coating with a withdrawal speed of 1 mm/s. These parameters yield the average surface roughness range of 0.3 to 0.5 µm achieved via dip-coating while also optimizing for time. Printing at 0.2 mm print resolution is two times faster than printing at 0.05 mm resolution in this specific study, yet both print resolutions yielded the same range of surface roughness when dip-coated with a withdrawal speed of 1 mm/s. Therefore, it is most efficient to 3D print a part quickly with the lower resolution of 0.2 mm because the surface quality can be recovered via dip-coating. The tradeoff for both time and dip-coating is small feature resolution. However, for the purpose of 3D printing as a manufacturing method for making molds and such, if a feature is small enough such that it is affected significantly by the dip-coating process, the feature is likely to be lost in the molding process as well. For example, due to the physics of thermoforming, sharp corners and features are not fully resolvable.

Overall, controlled dip-coating is found to be effective, to an extent, in improving the surface quality of SLA 3D printed parts. Though the dip-coating process itself was controlled, the results were variable and difficult to reproduce consistently. The variation in profilometer measurements were in part due to the method of measurement itself, making the angled faces horizontal, variable scan length due to part imperfections, etc.

6. Recommendations for Further Work

Regarding further work, it is recommended that the dip-coating process is carried out for different geometries of the test part in order to verify the effect of the angled faces on the surface. This work could potentially isolate the effects of the angled faces and the effects of the drainage as a result of the dip-coating process. Additionally, a different dip-coating solvent may be considered to minimize the effect of the surface tension causing the "bulge" seen in Figure 10.

Secondly, the curvature of the printed part's surface is another parameter to consider in characterizing the effectiveness of dip-coating as it will likely behave differently than a planar surface. It is important to note that for testing a non-planar surface, it may be more suitable to use an optical (non-contact) profilometer to have improved resolution in the 3D imaging of the surface profile. As mentioned in Section 3.3 Surface Roughness Measurements, the stylus (contact) profilometer is limited by the fact that the surface of interest must be horizontal, sacrificing measurement resolution if there is too much curvature or tilt. Additionally, the surface quality measurements will be dependent on the location of the measurement on the curvature due to the intrinsic layering in the 3D printing process.

To further the studies of part geometry/orientation and its effect on surface quality in combination with controlled dip-coating for application, the geometry on the smaller scale, such as texturing the surface, can be considered to control the thickness of the dip-coated layer. A particular work of interest done is this area outlined in "Coating of a textured solid" by Seiwert, Clanet, and Quéré. Controlling the thickness of the dip-coated layer will ultimately allow improved surface quality by smoothing out the printed layers without sacrificing tolerances or feature resolution on the printed part.

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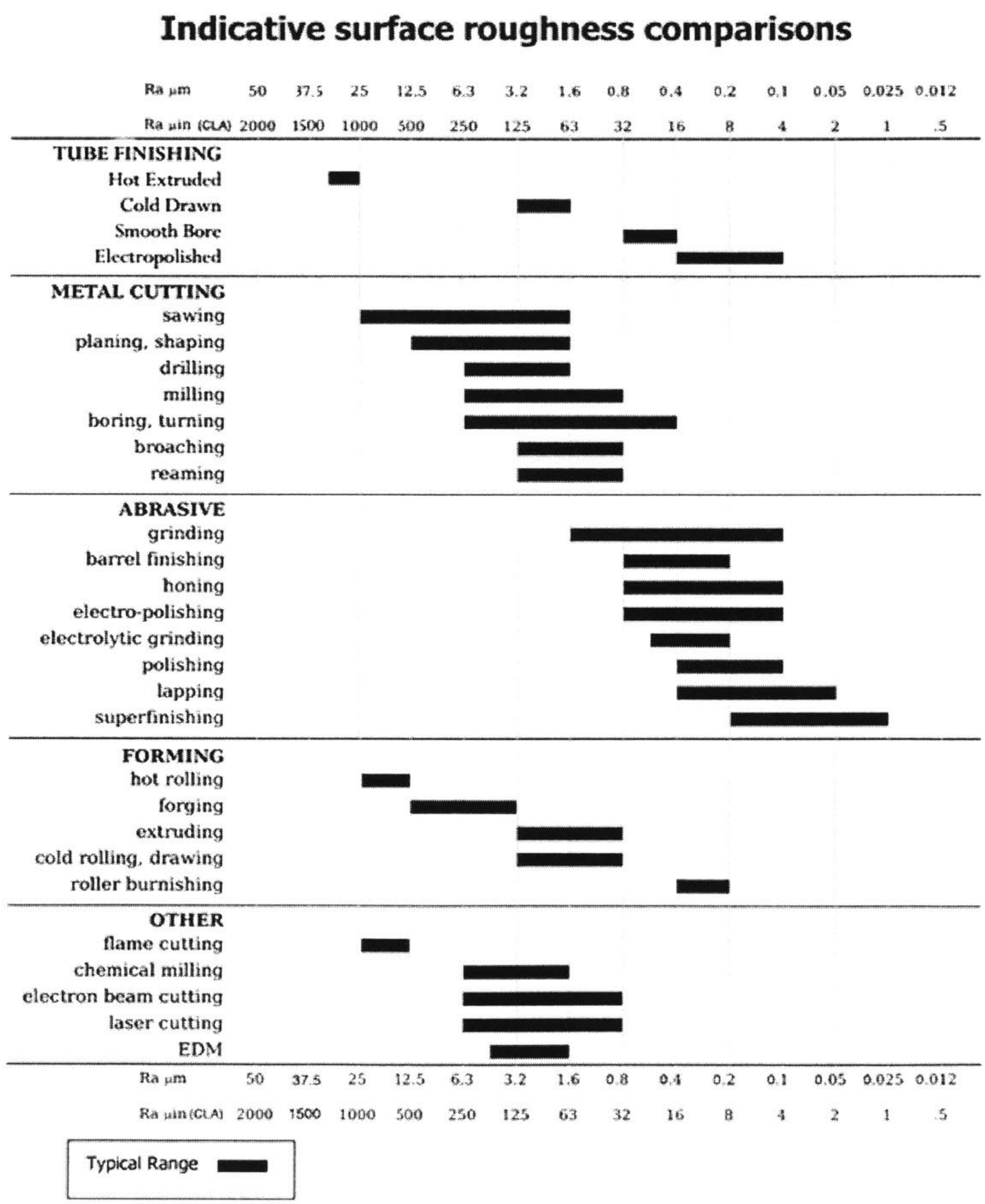
Appendix A: Controlled Dip-coating Code for use on Formlabs Form 1+ Printer

This is the code used to control the dip-coating process performed on the Formlabs Form 1+ Printer. The code uses the open source Formlabs OpenFL API for Form 1/Form 1+ Printer [16].

```
from OpenFL import FLP, Printer

def makeDipcoatSequence():
        """Return Packets that contains instructions for the dipcoat."""

        # Parameters
        vel = 1 # withdrawal rate in mm/s

        to_dip_cm = 6.2 # units = cm, distance from platform home;
                                        # print platform to touching top of container, fully immersing printed part

        part_length = 60 # units: mm; part height without supports + 3 mm buffer

        steps_per_mm = 400 # equal to 1 mm/s; parameter of printer's stepper motor

        # Calculations

        to_dip = to_dip_cm*10 # convert from cm to mm

        withdraw = float(vel)*steps_per_mm
        inrate = 5*steps_per_mm

        dipin = int(to_dip)*steps_per_mm # position of platform, immerse part into tank
        pullout = int(part_length)*steps_per_mm

        # commands to dip into tank and withdraw; note that velocity going in does not impact thickness of trapped layer
        # convert to Packets readable code for printer
        result = FLP.Packets()

        # dip part into resin tank
        result.append(FLP.ZFeedRate(usteps_per_s=inrate))
        result.append(FLP.ZMove(usteps=-dipin))
        result.append(FLP.WaitForMovesToComplete())

        # pull part out of resin tank at specified withdrawal rate
        result.append(FLP.ZFeedRate(usteps_per_s=withdraw))
        result.append(FLP.ZMove(usteps=pullout))
        result.append(FLP.WaitForMovesToComplete())

        # raise platform all the way to home position
        result.append(FLP.ZFeedRate(usteps_per_s=10000))
        result.append(FLP.ZMove(usteps=200000))
        result.append(FLP.WaitForMovesToComplete())

        return result


# get Printer object, i.e. connect to printer
p = Printer.Printer()
p.initialize()

# create Packets object for dipcoating seqence
dipcoat = makeDipcoatSequence()

# write dipcoating sequence to block for printing
block = 0
p.write_block(block, dipcoat)

p.start_printing(block)
```

Appendix B: Surface Roughness Comparison

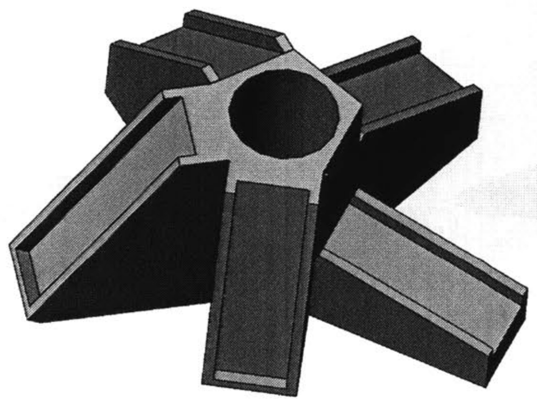
This is a chart showing relative surface roughness finishes with various manufacturing processes [14]. Note that they are approximate ranges as R_a depends on scan length. The R_a of the SLA 3D printed parts in this study without dip-coating were in the range of 0.5 to 1.8 µm and with dip-coating, in the range of 0.3 to 0.5 µm.



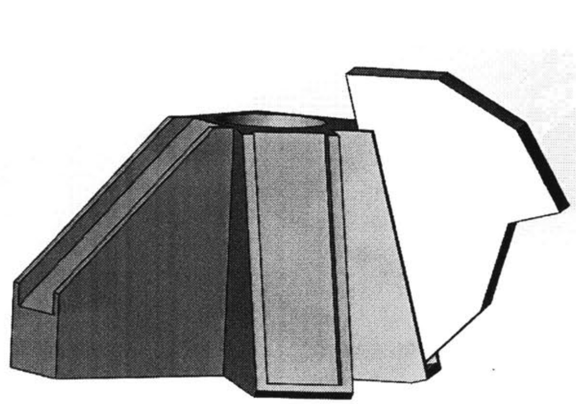
Appendix C: Angle Guide Design

This part was designed so that the different angles of the test part could be effectively horizontal so that the surface profile could be measured with a contact profilometer. The part is FDM 3D printed.

CAD



Assembly of angle guide and test part



All units below are in millimeters.