

Sanded FEP Films as Interface Layers in Inverted Vat Polymerization Additive Manufacturing

Hironori Kondo^{1*}

Contemporary three-dimensional printing, also referred to as additive manufacturing, has been popular for rapid prototyping due to its capacity for relatively facile design iteration and low investment per prototype. Object fabrication speeds, however, have lagged behind other manufacturing technologies, and existing approaches for accelerating the printing process are limited in their applicability and accessibility. This work explores the viability of using sanded FEP films as resin-irradiation window interface layers in inverted vat polymerization additive manufacturing for reducing layer separation requirements and expediting the printing process. The effects of sanding FEP films on the equilibrium contact angle of commercial vat polymerization resin on the FEP films are investigated, and the forces required to separate cured resin from the FEP films in a simulated inverted vat polymerization setup are explored. Scanning electron microscopy is used to reveal the effects of wear on these sanded surfaces. The findings of this work offer insight into methods for dramatically accelerating existing additive manufacturing and vat polymerization systems.

¹Taipei American School, 800 Chung Shan North Road, Section 6, Taipei, Taiwan 11152

*Corresponding author. Email: 21hironorik@students.tas.tw

INTRODUCTION

Three-dimensional (3D) printing has garnered much attention in recent years. Its first major (and often eponymous) use case traces back to "rapid prototyping" (1–5), the process of quickly creating iterations of a physical prototype. Today, 3D printing is used in a variety of applications, ranging from the medical sphere to manufacturing (2–4, 6–9).

In more technical cases, the technology is often referred to as "additive manufacturing" (AM), an internationally, industrially-standardized term (1). As defined in its standard, AM describes processes that use "successive addition" (as opposed to removal, casting, etc.) of material, often done in discrete layers, to form physical objects. This work addresses limitations in existing AM processes to expedite this process of material addition.

The appeal of AM for prototyping stems from its removal of tooling (i.e. the machining of molds and other manufacturing aids) and complex setup requirements characteristic of other manufacturing technologies, enabling relatively facile design

iteration with lower investments for each prototype (2–4, 8, 10). Despite AM being referred to as "rapid", however, the actual process of printing is often slower than formative and subtractive manufacturing technologies. As such, speed stands as one of modern AM's most critical limitations (3, 4, 9–12).

For addressing this limitation, the vat polymerization (VP) printing technology (1) is of particular interest, as, unlike other forms of AM, VP does not require each layer (i.e. cross section of the print) to be traced by a focused energy source or extrusion/jetting device. At its most basic, VP is a process in which a light-reactive, liquid photopolymer feedstock is selectively cured in a vat, forming a solid part (1). Being light-catalyzed (typically by ultraviolet, or UV, light), VP creates the possibility of irradiating a full layer at once by selective light exposure, with no moving printing head or focused, high-power energy source necessary. A typical inverted VP machine (the most common style for modern machines) is depicted in Fig. 1.

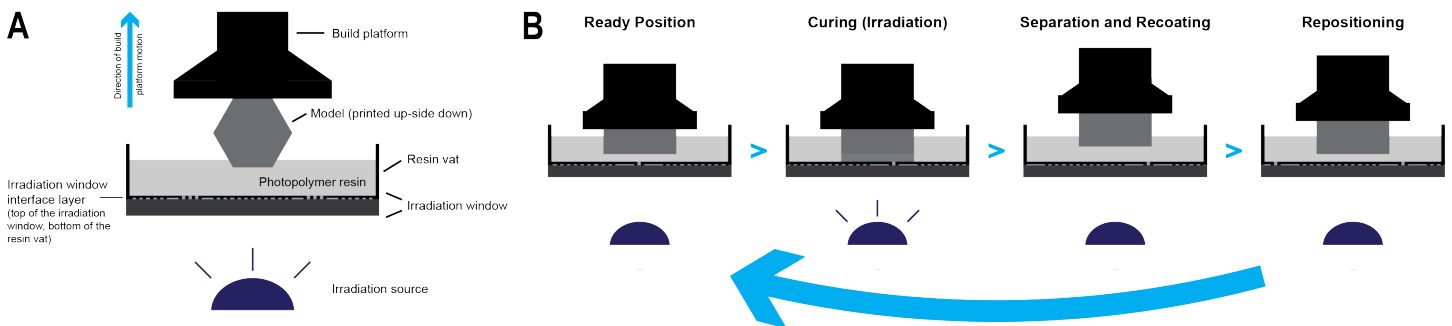


Fig. 1. Diagram of a typical inverted VP machine. (A) Diagram of the components of a typical inverted VP setup. Printed models are pulled out of the resin vat, up-side down. **(B)** Flowchart of a typical inverted VP printing process. Each layer is cured by irradiation in the space between the build surface and irradiation window interface layer. After curing, the print is separated from the interface layer, which is given time for recoating by resin. The build platform is then repositioned for the curing of the next layer.

Current Approaches to Continuous VP

As VP enables an entire cross-sectional area to be exposed at once, the separation and recoating steps (Fig. 1B) for each layer of a potentially several-thousand-layer 3D print offer a considerable opportunity to reduce print time. Such "continuous printing" was described in a patent filed in 2006, which proposed a "layerless" printing system with uninterrupted irradiation (13). Since then, several attempts have been made to achieve this by altering the interface layer (Fig. 1A) such that newly cured resin does not adhere it. In standard, non-continuous machines, this layer is made of some material to which resin adheres relatively poorly, typically a fluorinated ethylene propylene (FEP) film. While this does reduce the mechanical forces of separation, it does not eliminate the need for the separation step. The current approaches for continuous printing replace this interface layer to fully eliminate the need for separation.

One successful approach has been the use of an oxygen-permeable irradiation window (12, 14, 15). Oxygen inhibits the polymerization reaction, resulting in a polymerization-free zone directly above the window that prevents resin-interface adhesion and allows for a continuous flow of fresh resin for recoating.

A more recent approach by Northwestern University has been replacing the interface layer with continuously flowing "liquid Teflon" (16). The non-stick liquid continuously circulates over the irradiation window, both eliminating adhesion and removing heat from the polymerization reaction.

A team from the University of Michigan has also achieved continuous printing, but instead of altering the interface layer, they have formulated a photopolymer resin that incorporates polymerization inhibitors (17). By using two wavelengths of light, one for polymerization initiation and another for polymerization inhibition, they have also achieved a polymerization-free zone above the irradiation window.

While certainly successful, these methods of achieving continuous printing necessitate large amounts of proprietary, in many cases patented or minimally disclosed, hardware and software, limiting the accessibility of these technologies. While this may be acceptable for the industrial applications that many of these systems were developed for, increasing the speed of AM for the average consumer of the technology will require more accessible forms of continuous printing. As current literature surrounding such non-industrially-oriented methods of expediting AM is limited, further exploration is needed. This research tests the viability of a drop-in replacement for existing FEP interface layers that may address this deficiency.

Theory

The basis for the theory of this research draws inspiration from previous studies that have demonstrated the possibility of producing superhydrophobic polytetrafluoroethylene (PTFE) surfaces via sanding (18, 19). The principle behind these studies lies in the widely-proven Wenzel (20) and Cassie-Baxter (21) models of wetting.

Under the Wenzel state, a drop of water resting on a solid surface conforms to the irregularities of the surface, forming solid-liquid interfaces and a fully-wetted state, as depicted in Fig. 2A (20). This is modeled by the following equation, where θ_w is the equilibrium contact angle, θ the contact angle as calculated from Young's Law, and r the roughness ratio (to account for surface roughness):

$$\cos(\theta_w) = r \cos(\theta) \quad (1)$$

Given sufficiently closely spaced microfeatures on a surface and a sufficiently low liquid pressure, a Cassie-Baxter state of wetting is possible. In this state, air is "trapped" in the roughness of a naturally hydrophobic surface, and air-liquid interfaces are created, as shown in Fig. 2B (21). The equilibrium contact angle, θ_{cb} , can be derived from the contact angle as calculated from Young's Law, θ , and the fractional surface area of the drop on the surface, σ :

$$\cos(\theta_{cb}) = \sigma(\cos(\theta) + 1) - 1 \quad (2)$$

As a superhydrophobic state represents relatively low molecular attractions of water to the solid surface, this approach to modifying PTFE is of interest for the FEP interface layers used in many VP machines. Having a fully-fluorinated and weakly polar molecular structure similar to that of PTFE, FEP is likely to exhibit similar hydrophobic properties, which may affect the contact angles of VP resin on FEP and the separation forces experienced while printing. This is especially valuable given that most commercial 3D printing resins are known to dissolve in isopropyl alcohol, a polar solvent, which suggests that the vast majority of commercial resins across varying material compositions may all behave similarly with water (which, too, is polar) when placed in contact with FEP.

This research tests the viability of such sanded FEP films for reducing, or even eliminating, separation requirements in VP, which would offer a simple drop-in replacement for existing FEP films with much simpler integration than existing attempts at high-speed, continuous VP.

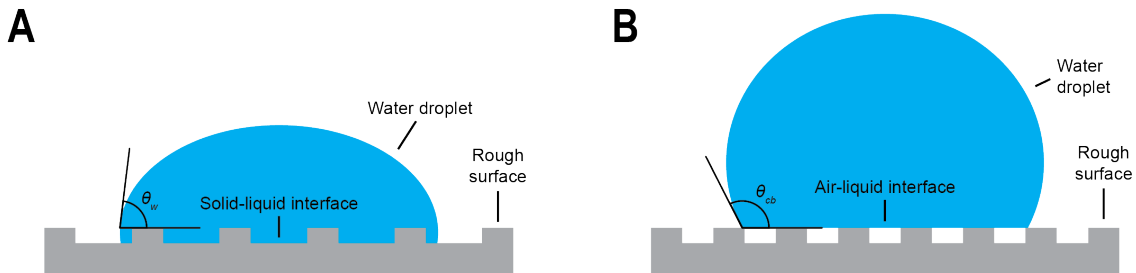


Fig. 2. Wetting of rough surfaces. (A) A model of a water droplet in the Wenzel state, where the water conforms to the solid surface and forms only solid-liquid interfaces. θ_w is the equilibrium contact angle. **(B)** A model of a water droplet in the Cassie-Baxter state, where air-liquid interfaces are sustained. θ_{cb} is the equilibrium contact angle.

MATERIALS AND METHODS

To test the efficacy of sanded FEP interface layers for minimizing separation requirements in VP, data collection comprised of two experiments: the first measured the equilibrium contact angle of commercially-available VP resin on samples of sanded FEP and a non-sanded control, and the second measured the force required to separate a layer of irradiated resin from identically-prepared FEP surfaces in a setup mimicking a typical inverted VP printing process. These experiments provided insight into a) the interactions between the resin and the FEP surfaces, and b) the actual behavior of the two in a physical application, respectively.

FEP Preparation

The FEP surfaces used in both experiments were prepared with commercially-available FEP films for VP 3D printers. The films were 200 μm thick, on the thicker end of what is typically seen in a VP machine to account for the slight removal of material from the sanding process. The films were sliced into 12 rectangular strips of 40 mm by 90 mm. One was reserved for a control, and the other 11 were sanded.

For sanding, a Black and Decker random orbital sander was used to mitigate directional biases in the sanding pattern and to create more uniform, consistent surfaces. It is critical to note that existing literature has found the final hydrophobic properties of sanded PTFE to be unaffected by the use of a mechanical sander as opposed to sanding by hand

(18). The sander was mounted on its side and given sandpaper from the same manufacturer and product line of ISO/FEPA grit designations (a measure of coarseness, where a lower number indicates higher coarseness) of 60, 80, 150, 180, 240, 320, 400, 600, 800, 1000, and 1500 for each of the 11 samples that were sanded. Each sample was pressed, from the center, against the moving sanding pad until a uniformly-sanded surface was achieved.

After sanding, the samples were rinsed with acetone and distilled water to remove residual dust and particles on the surfaces.

Two sets of samples were prepared with the procedure described, one for each experiment. The use of separate samples was to mitigate differences in behavior between experiments caused by the potential effects of FEP wear.

Photopolymer Resin Preparation

The experiments used commercially-available, methacrylate-based Standard White Resin from Formlabs, a popular producer of professional VP machines. A popular commercially-available resin of the common methacrylate base (22), as opposed to a custom-formulated one of known composition but more limited practical applicability, was selected to better simulate real-world use and incorporate functional additives, as found in many commercial products. A portion of the resin was poured into a UV-opaque dropper bottle for use. A UV-opaque bottle was chosen to prevent the resin from curing while not in use.

Testing Apparatus

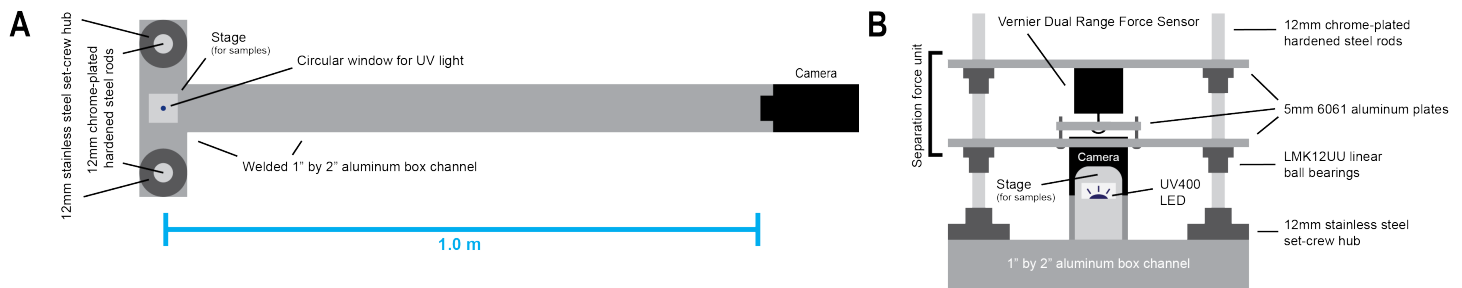


Fig. 3. Diagram of the testing apparatus (not to scale). (A) Top view of the testing apparatus. Separation force unit (Fig. 3B) not depicted to provide a view of the stage. Samples are placed on the stage for testing. A circular window in the stage allows light from the UV light-emitting-diode (LED) (Fig. 3B) through. (B) Front view of the testing apparatus. Separation force unit measures separation forces of cured resin from FEP samples. The unit consists of two sets of aluminum plates and LMK12UU linear bearings riding on 12 mm steel rods, connected by a Vernier Dual Range Force Sensor. The camera is depicted in the background.

The testing apparatus (Fig. 3) was designed to accommodate both experiments: to measure equilibrium contact angles of resin on FEP samples (Experiment 1), as well as separation forces of cured resin from identically-prepared samples in a mock inverted VP setup (Experiment 2). It was constructed from a welded aluminum box-channel (a standardized form of extruded aluminum) frame for appropriate rigidity and repeatability.

Typically, contact angles are measured with specialized equipment, such as a contact angle goniometer. However, as no goniometers were available for use, a similar setup was created with an LED backlight and camera. In principle, the camera

would provide side views of sample drops, with contrast provided by the backlight. The resulting images could then be imported into an image analysis tool for determination of the contact angles. Ideally, the images would provide perfectly orthogonal (i.e. side-on) views of the drops, as this mitigates distortion and enables the most accurate analysis; unfortunately, such ideal views are not possible with a typical camera, where light enters the lens at a range of angles. As depicted in Fig. 4, however, the further a subject is from the lens, the closer to parallel the incoming light rays will be, forming a closer-to-orthogonal image:

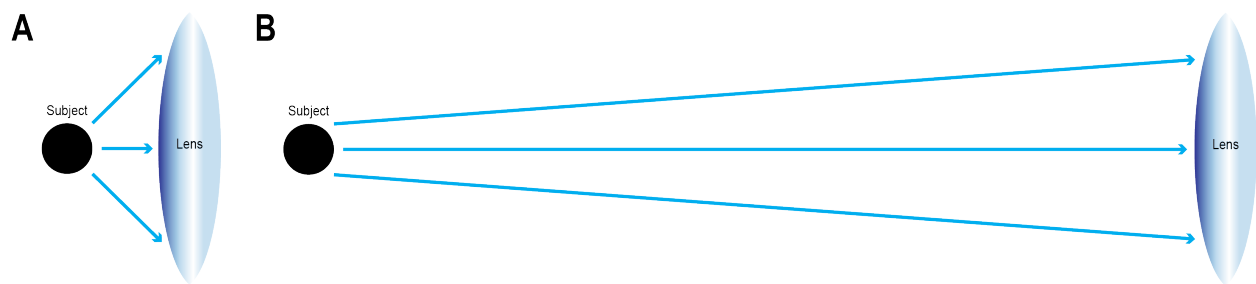


Fig. 4. Simplified illustrations on the effect of increased subject distance on the orthogonality of the resulting image. (A) A depiction of a relatively near subject. Light rays from the subject (simplified for illustrative purposes) enter the lens at varying angles. (B) A depiction of a relatively distant subject. Light rays from the subject (again simplified) enter the lens at a smaller range of angles, providing a view that is closer to being perfectly orthogonal.

In reality, the distance of the subject from the lens is limited by the magnification of the lens and the resolving power of the camera that is used, as enough detail must be preserved at the edge of the resin drops for image analysis. For this investigation, a Canon EOS M50 camera with a 55 mm to 200 mm lens was available. A sufficiently reasonable focal length (out of the available range of 55 mm to 200 mm) for the setup was determined to be 135 mm, which provided a relatively optimal balance between magnification and minimum focusing distance (the minimum distance from the lens at which it is able to focus the image); lower focal lengths required the camera to be placed closer to yield larger and more detailed images of the samples, while higher focal lengths increased the minimum focusing distance by more than the extra magnification made advantageous, requiring the camera to be placed too far to achieve a large enough image. Based on this focal length, the testing apparatus was designed to have the camera secured 1.0 meters from the center of the sample stage via a typical tripod screw, just outside of the minimum focusing distance (Fig. 3A). The ISO was set to 100, the lowest setting available, to minimize noise in the images without needing later edits. Aperture and shutter speed were set at $f/6.3$ and $1/640$ seconds, respectively. The camera was controlled wirelessly through Canon's EOS Utility 3 software to minimize physical contact with and unwanted motion of the camera during shooting. The ImageJ 1.46r program with its Contact Angle plugin was used as the image analysis tool.

To measure separation forces, a mock inverted VP setup was created around the sample

stage, which was designed in computer-aided-design software Autodesk Fusion 360 and 3D printed in polylactic acid plastic. The setup involved two components: a separation force unit responsible for the measurements, and a set of linear rods to provide a restricted axis of motion for the unit (Fig. 3B). For the linear rods, a pair of 12 mm chrome-plated hardened steel rods were used for rigidity and smooth motion, and each was mounted with a 12 mm stainless steel set screw hub. This setup ensured that the separation force unit would only measure forces perpendicular to the samples. For the separation force unit, two independent assemblies of 5 mm aluminum plates were physically connected via a Vernier Dual Range Force Sensor set to $\pm 10\text{N}$, which was wired to a Vernier LabPro sensor interface (Fig. 3B). By having the force sensor as the only physical connection between the two sliding assemblies, differences in the forces experienced by the assemblies would be picked up by the sensor. The bottom assembly mimicked the build plate in an inverted VP machine, providing a surface onto which the resin could cure. Upward movement of the top assembly would apply force to the bottom assembly and the cured resin through the sensor, data from which was plotted in the Logger Pro 3.14.1 software via a USB connection between the LabPro interface and a computer. Each aluminum assembly rode on the linear rods via their own pairs of well-greased LMK12UU linear ball bearings for smooth motion (Fig. 3B).

Both experiments required that resin be cured, so a 400-nanometer UV LED was placed under the sample stage. A 5 mm hole was designed into the

center of the stage via Autodesk Fusion 360 to allow the light through. An Adafruit Pro Trinket 5V microcontroller board was programmed in the C++ programming language via the Arduino 1.8.10 IDE software to precisely control the time of irradiation of the LED.

Testing Method: Contact Angle (Experiment 1)

To test for contact angle, each FEP sample was placed onto the sample stage, and a drop of photopolymer resin was deposited at its center, concentric with the hole in the stage such that it would be evenly irradiated. After given time for the drop to settle, a photograph of the drop was taken. The curing cycle, as controlled by the Pro Trinket microcontroller, was then started, with three cycles of the UV LED turning on for 3.000 seconds and then off for 1.000 seconds. In each 1.000 second gap between UV-on time, a photograph of the resin drop was taken, such that a total of four images were taken for each drop. These images provided contact angle data for the resin drops before, during, and after curing.

The above procedure was repeated for all 12 FEP samples. This was then repeated two more times for a total of three trials and three sets of 48 images each, with the FEP samples rinsed with acetone to remove resin and dried with compressed air between trials. The images were imported into ImageJ, where they were each identically cropped, and the Manual

Points Procedure of the Contact Angle plugin was run on each drop. The complete data set was exported from ImageJ as a Microsoft Excel file. The "ThetaE" value provided by ImageJ was used to create a separate graph for each trial (Fig. 5).

Testing Method: Separation Forces (Experiment 2)

To measure separation forces, each FEP sample was clamped onto the sample stage, and a drop of photopolymer resin was deposited at its center, concentric with the hole in the stage such that it would be evenly irradiated. The separation force unit was lowered gently onto the stage, as would be the case in mechanized VP. The new curing cycle of 9.000 seconds was initiated.

After irradiation, data collection was started in Logger Pro and the top assembly of the separation force unit was pulled upwards until successful separation of the bottom assembly from the FEP sample. The run was labeled and stored within the Logger Pro file.

The above procedure was repeated for all 12 FEP samples. This was then repeated two more times in new Logger Pro files each time, resulting in three total trials and three total files of 12 curves each. The samples were rinsed with acetone to remove resin and dried with compressed air between trials. The average force for each sample across the three trials was plotted in a single graph (Fig. 6).

RESULTS AND DISCUSSION

The results of the contact angle experiment show increasing contact angles with increasing roughness (decreasing grit) for the first trial (Fig. 5A), an inconsistent and poor apparent correlation between contact angle and roughness for the second trial (Fig. 5B), and slightly decreasing contact angles with increasing roughness for the third trial (Fig. 5C). The non-sanded (control) contact angles are relatively consistent between trials at just over 70 degrees (Fig. 5).

As the non-sanded contact angle is consistently less than 90 degrees, the FEP is shown to be naturally attracted to the resin, and the Wenzel state of wetting is expected as the surface roughness increases. This would correlate to decreasing contact angles, which is only vaguely observed in trial three (Fig. 5C). The second trial does not seem to establish a clear correlation between the two variables (Fig. 5B), and the first trial appears to contradict the expected behavior (Fig. 5A).

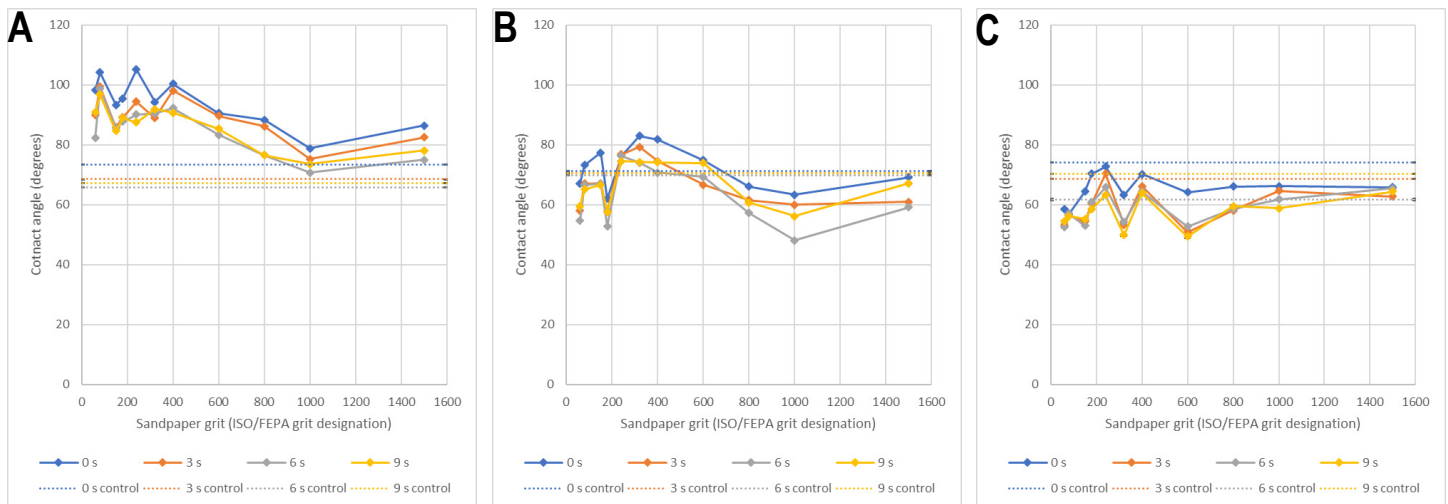


Fig. 5. Contact angles of resin on sanded FEP samples and a non-sanded control varying by seconds (s) of irradiation. (A) For trial one. (B) For trial two. (C) For trial three.

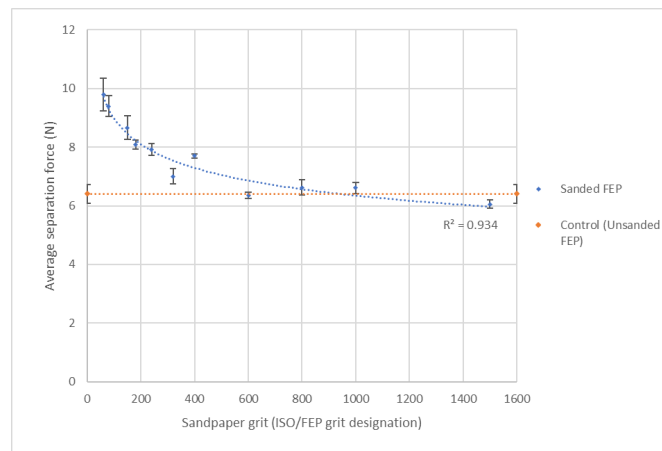


Fig. 6. Average separation forces of cured resin from sanded FEP samples and a non-sanded control.

A potential explanation for this would be wear of the sanded surfaces. Newly-sanded FEP surfaces, after rinsing with acetone, were "fuzzy" visually and to the touch. This "fuzziness" was less prominent in used samples, which still displayed roughness and texture from the sandpaper, but did not have the thin, hair-like projections of the new samples. To verify these observations, a new, follow-up test was conducted. A new 80-grit sample was prepared in the same manner as the other samples, and it and a used 80-grit sample from Experiment 1 were viewed under a Phenom G2 scanning electron microscope (SEM), which provided detailed images of the samples' surfaces. A single-topography view, as opposed to the combined view, was selected in the microscope settings for clearer depth and structure depiction. 80-grit samples were selected for their generally rougher surface, which would provide more identifiable surface features in the SEM images. 60 and 100-grit samples would have also served well.

In the images (Fig. 7), the fresh sample (Fig. 7A) is characterized by thin, wispy structures with sharp edges and points that stand up from the surface, while the used sample (Fig. 7B) shows these structures more matted down and with seemingly smooth, rounded-over edges. These structures match the observed surface "fuzz", and the matted, smoothed-over structures of the used sample seem indicative of the wear previously postulated. It is conceivable that the standing structures of the fresh samples supported the drops of resin, preventing them from being in full contact with the actual surface of the FEP, thus increasing the perceived contact angle. A coarser (lower) grit of sandpaper would cause greater removal of material and greater "fuzziness", which in turn would increase the perceived contact angle. This aligns with the trend observed in trial one (Fig. 5A). After use, however, this "fuzz" is reduced as the hair-like structures are seen to be matted down

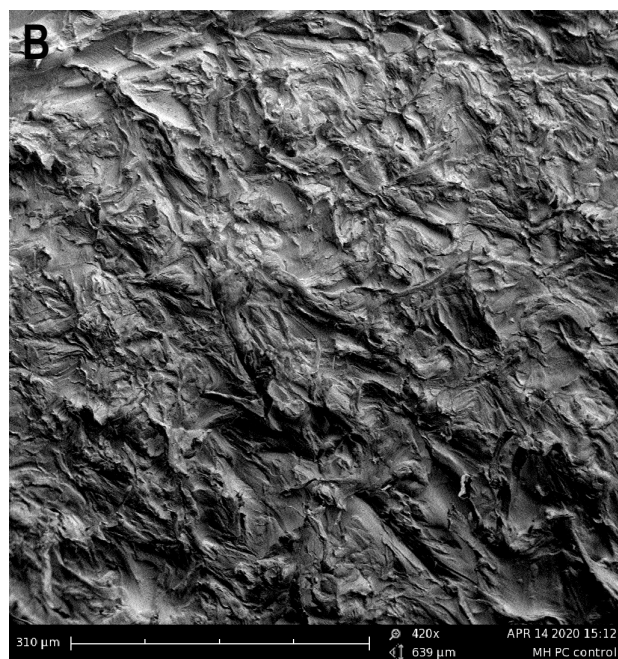
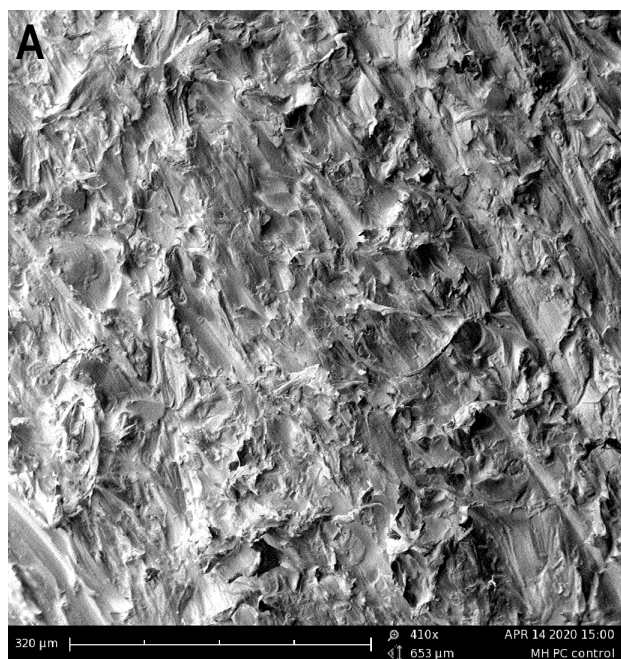


Fig. 7. Single-topography SEM images of FEP samples sanded with 80-grit sandpaper. (A) For a fresh, unused sample. (B) For a used sample from Experiment 1.

and smoothed over (Fig. 7B), thereby increasing the amount of resin that is exposed to the actual FEP surface. As such, repeated use of the FEP would cause the expected theoretical behavior to emerge. The data gradually shifts from an apparently contradictory relationship to a more expected behavior in trial three, which aligns with this theory (Fig. 5C). As such, the data and SEM images suggest that, for long-term use, the sanding of FEP results in lower contact angles than typical non-sanded films, with wetting occurring in the Wenzel state.

All three trials also rather consistently demonstrate higher contact angles for uncured resin (0 s) relative to the various stages of cured resin (3 s, 6 s, 9 s) (Fig. 5). The prevalence of this behavior across all three trials suggests that it is independent of the "fuzziness" that appears to have caused the discrepancies already described. Instead, it appears to indicate that, regardless of "fuzziness" and contact angle, the breaking and formation of molecular bonds in the curing process generates either a greater attraction between the resin and FEP film or a greater conformation of the resin to the FEP surface. For VP, this is a valuable observation, as the main concern for speeding up the printing process is the degree of attraction of cured resin to the FEP.

The separation force experiment revealed that lowering grit (and increasing roughness) was correlated to higher separation forces (Fig. 6). Only two average separation forces, from the 600 and 1500 grit samples, were lower than that of the non-sanded control, but the difference is not enough relative to the respective standard errors to yield any substantial conclusions. The results of this experiment align with that of the contact angle experiment, which demonstrated a Wenzel state of wetting. In the Wenzel state, the area of contact between resin and FEP would be higher for lower sandpaper grits, yielding higher total adhesion, which is observed. The consistency of the data, as revealed by the steady trend and low standard errors, also appears to suggest that the "fuzziness" critical to the contact angle data did not have a major influence on the separation force data. The difference between the two experiments is the presence of the separation force unit resting on the sample stage, suggesting that the increase in pressure caused by the lowering of the separation force unit led to a conformation of the resin to the FEP surface, regardless of surface "fuzziness" and FEP wear. This data reveals that sanded FEP, even when previously unused and displaying improved contact angles, bears no practical benefits for reducing actual separation forces in VP.

CONCLUSIONS AND FUTURE DIRECTIONS

Conclusions

This research explored the potential of using sanded FEP, inspired by superhydrophobic sanded PTFE (18, 19), as a means to accessibly and inexpensively reduce separation forces (Fig. 1B) in inverted VP. Two experiments were conducted to this end, the first measuring the contact angles of commercial VP resin on samples of sanded FEP and a non-sanded control, and the second measuring the force of separating cured resin from identically-prepared FEP samples and a non-sanded control in a setup mimicking that of a typical inverted-VP machine.

The first experiment revealed that VP resin naturally forms contact angles of less than 90 degrees with FEP (Fig. 5). Thin, hair-like "fuzz" on the surfaces of FEP samples appears to cause increases in apparent contact angles after sanding (Fig. 5A), but this "fuzz" quickly wears away with use, and the resin assumes the expected Wenzel state of wetting, with lower contact angles caused by sanding (Fig. 5C). The process of curing the resin is shown to decrease the contact angles (Fig. 5).

The second experiment revealed that separation forces are increased by sanding (Fig. 6). This is shown to occur independently of the observed FEP "fuzz", with results aligning with the expected Wenzel state of wetting. A plausible explanation of this behavior is that the increase in pressure caused by the lowering of a build plate increases the resin's conformation to the FEP surface, mitigating the effects of the "fuzz". Thus, sanding of FEP is shown to have practical drawbacks for VP.

Limitations

While it seems qualitatively conclusive that sanded FEP interface layers do not offer substantial benefits for continuous printing, there were inherent limitations to the testing procedure that could be addressed for more consistent data and the potential resolution of discrepancies.

An important observation and anomaly of the contact angle experiment was that the contact angles increased with surface roughness in the first trial (Fig. 5A). The possible explanation of surface "fuzz" and wear of this "fuzz" is proposed and identified, but further exploration into the effects of varying sandpaper grits and sanding methods on this "fuzz" and how it affects FEP-resin interactions would be valuable for a deeper understanding of the observed behavior.

Additionally, the contact angle experiment was critically lacking in equipment, potentially explaining the inconsistent data. A contact angle goniometer was not available for the contact angle images, decreasing the precision and repeatability of the experimental setup. An eye dropper bottle was used for depositing resin, which can consistently provide drops of similar sizes, but the volume cannot be precisely controlled beyond the natural effects of gravity. Drop volume plays a role in the contact angle of each drop, so better control would also benefit precision. The Contact Angle plugin of ImageJ is also inherently limited, as it cannot account for curvatures in samples' surfaces. Instead, it assumes perfectly flat surfaces, which can skew calculated

contact angles on surfaces that are deformed or warped. Better control of the flatness of the samples, especially after the sanding process, or the inclusion of surface curvature in image analysis would yield more consistent contact angle data.

The main limitation of the separation force experiment was that only one drop of resin was used for each trial. In practical applications, the separation step of VP occurs in a vat of resin, where the irradiated region is surrounded by unirradiated resin. The experiment was not able to account for the interactions of the irradiated resin with the surrounding volume, nor potential differences in pressure caused by the uncured resin above the layer being irradiated.

Future Directions

This work reveals that wetting of FEP by VP resin occurs naturally in the Wenzel state, and the possibility of forming air-liquid interfaces characteristic of the Cassie-Baxter state is limited by the increase in pressure caused by the lowering of the build plate in standard inverted VP. As VP resin is shown to consistently conform to the irradiation window interface layer (Fig. 1A), and non-sanded FEP film already naturally offers a very smooth

surface with low surface area, the use of wetting properties for the reduction of separation forces and the acceleration of the VP printing processes appears impractical. For further pursuits in continuous VP, this approach may offer limited avail.

Rather, the implication of this work is that the reduction and elimination of separation forces appears to require an alternate approach, perhaps via an active repulsion of the resin from the interface layer, possibly electromagnetically, or the prevention of curing in the area immediately adjacent to the interface layer. The existing methods of eliminating separation forces (12, 14–17) already employ the latter of these approaches, but in limitedly-accessible ways. A solution of this form would require a unique approach that does not have the hardware and software limitations of the existing solutions.

To these ends, a closer observation of resin behavior, especially when interacting with interface layers, on a molecular level may prove beneficial, especially as the curing of the resin is shown to decrease contact angle (Fig. 5). A possible area to explore would be the physical disturbance, instead of chemical inhibition, of the resin near the interface layer, perhaps by minute, likely micrometer-scale, and consistent, or otherwise carefully-timed, vibrations of the interface layer.

REFERENCES AND NOTES

1. ISO/ASTM, ISO/ASTM 52900:2015 [ASTM F2792] Additive manufacturing — General principles — Terminology. *ISO*, (available at <http://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/96/69669.html>).
2. H. Lipson, M. Kurman, *Fabricated: The New World of 3D Printing* (John Wiley & Sons, 2013).
3. T. Campbell, C. Williams, O. Ivanova, B. Garrett, "Could 3D Printing Change the World?: Technologies, Potential, and Implications of Additive Manufacturing" (Atlantic Council, 2011), (available at www.jstor.org/stable/resrep03564).
4. T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, D. Hui, Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*. **143**, 172–196 (2018).
5. I. Gibson, D. W. Rosen, B. Stucker, in *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, I. Gibson, D. W. Rosen, B. Stucker, Eds. (Springer US, Boston, MA, 2010; https://doi.org/10.1007/978-1-4419-1120-9_1), pp. 20–35.
6. I. Gibson, D. W. Rosen, B. Stucker, in *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, I. Gibson, D. W. Rosen, B. Stucker, Eds. (Springer US, Boston, MA, 2010; https://doi.org/10.1007/978-1-4419-1120-9_15), pp. 400–414.
7. I. Gibson, D. W. Rosen, B. Stucker, in *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, I. Gibson, D. W. Rosen, B. Stucker, Eds. (Springer US, Boston, MA, 2010; https://doi.org/10.1007/978-1-4419-1120-9_14), pp. 378–399.
8. S. H. Huang, P. Liu, A. Mokasdar, L. Hou, Additive manufacturing and its societal impact: a literature review. *Int J Adv Manuf Technol*. **67**, 1191–1203 (2013).
9. W. Gao, Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C. B. Williams, C. C. L. Wang, Y. C. Shin, S. Zhang, P. D. Zavattieri, The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*. **69**, 65–89 (2015).
10. S. Mellor, L. Hao, D. Zhang, Additive manufacturing: A framework for implementation. *International Journal of Production Economics*. **149**, 194–201 (2014).
11. W. Oropallo, L. A. Piegler, Ten challenges in 3D printing. *Engineering with Computers*. **32**, 135–148 (2016).
12. J. R. Tumbleston, D. Shirvanyants, N. Ermoshkin, R. Januszewicz, A. R. Johnson, D. Kelly, K. Chen, R. Pinschmidt, J. P. Rolland, A. Ermoshkin, E. T. Samulski, J. M. DeSimone, Continuous liquid interface production of 3D objects. *Science*. **347**, 1349–1352 (2015).
13. A. Shkolnik, A. El-Siblani, H. John, Continuous generative process for producing a three-dimensional object (2011), (available at <https://patents.google.com/patent/US7892474/en?q=7%2c892%2c474>).
14. R. Januszewicz, J. R. Tumbleston, A. L. Quintanilla, S. J. Mechem, J. M. DeSimone, Layerless fabrication with continuous liquid interface production. *PNAS*. **113**, 11703–11708 (2016).
15. W. Zhu, K. R. Tringale, S. A. Woller, S. You, S. Johnson, H. Shen, J. Schimelman, M. Whitney, J. Steinauer, W. Xu, T. L. Yaksh, Q. T. Nguyen, S. Chen, Rapid continuous 3D printing of customizable peripheral nerve guidance conduits. *Materials Today*. **21**, 951–959 (2018).
16. A. Morris, Highest-throughput 3D printer is future of manufacturing (2019), (available at <https://news.northwestern.edu/stories/2019/10/biggest-fastest-3d-printer-is-future-of-manufacturing/>).
17. M. P. de Beer, H. L. van der Laan, M. A. Cole, R. J. Whelan, M. A. Burns, T. F. Scott, Rapid, continuous additive manufacturing by volumetric polymerization inhibition patterning. *Science Advances*. **5**, eaau8723 (2019).
18. M. Nilsson, R. Daniello, J. Rothstein, A novel and inexpensive technique for creating superhydrophobic surfaces using Teflon and sandpaper. *Journal of Physics D: Applied Physics*. **43**, 045301 (2010).
19. D. Song, R. Daniello, J. Rothstein, Drag reduction using superhydrophobic sanded Teflon surfaces. *Experiments in Fluids*. **55** (2014), doi:10.1007/s00348-014-1783-8.
20. R. N. Wenzel, RESISTANCE OF SOLID SURFACES TO WETTING BY WATER. *Ind. Eng. Chem*. **28**, 988–994 (1936).
21. A. B. D. Cassie, S. Baxter, Wettability of porous surfaces. *Trans. Faraday Soc*. **40**, 546 (1944).
22. White Photoreactive Resin for Formlabs 3D printers: Safety Data Sheet, (available at https://archive-media.formlabs.com/upload/White_Resin_SDS_EU.pdf).

Acknowledgments: The author is grateful to Mr. Leandro Lopez and Dr. Candace Aiani of Taipei American School for consultation. The author thanks Mr. Jude Clapper, Director & MC Esher Chair of Scientific Research, Taipei American School, for recommending and guiding scanning electron microscopy. The author thanks Mr. Jaami Franklin, Political Science & Forensics Department Chair, Taipei American School, for funding.

Funding: This work was supported by the Taipei American School Political Science & Forensics Department.

Competing interests: The author declares that no competing interests exist.

Data and materials availability: All data needed to evaluate the conclusions in the work are present in the work. Further data and materials relating to this work may be requested from the author.