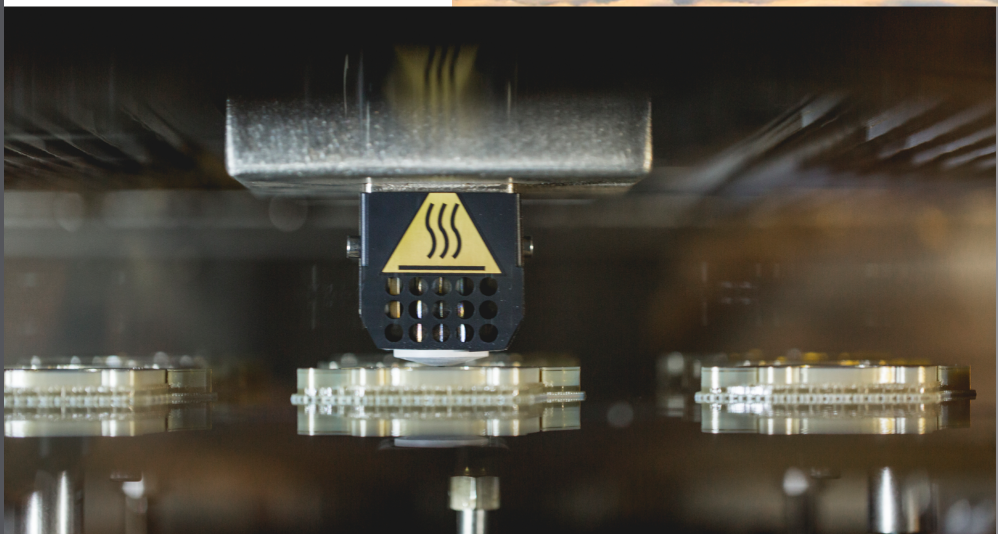
# 3D Printed Aerospace Parts

Bringing behind the scenes parts into the spotlight



3D Printed Aerospace Parts White Paper

## Comprehensive Study on VaperFuse Surfacing

The aerospace industry was an early adopter of additive manufacturing. The design freedom & material options made it attractive for applications like environmental control ducting. While the properties, parts, and accuracy have exceeded expectations and proven highly accurate, part esthetics have remained time-consuming and costly, leaving parts hidden from view behind panels and shrouds.

Aerospace parts have been hidden because the inherent layer lines from processing are different than the expected surface from a traditionally manufactured part. The disconnect between the expectation of a glossy smooth injection molded part and the reality of an additively produced part has left designers placing parts in unseen locations. When designers want to have additively produced parts in plain sight, they are forced to rely on manual finishing techniques that drive costs up significantly.

To address this limitation and enhance the overall quality of aerospace components, Stratasys Direct Manufacturing joined forces with DyeMansion to conduct a comprehensive study. The primary focus of the investigation was to explore the benefits of VaporFuse Surfacing (VFS) in improving the esthetics and performance of aerospace parts made from two commonly used materials: ULTEM™ 9085 resin & FR106. Both materials have been trusted for many different aerospace applications for years and are among the top material choices due to their flame retardance and mechanical properties.

This whitepaper presents the findings from this study, shedding light on how vapor smoothing processes can significantly impact the surface finish, sealing capabilities, and mechanical properties of 3D printed aerospace parts. The results from this investigation offer valuable insights to industry professionals, engineers, and designers, as they seek to leverage the full potential of additive manufacturing in aerospace applications. The objective of this study is to establish a baseline of mechanical, flammability, and dimensional stability for aerospace-driven materials after they have been put through Vapor Fuse Surfacing.

*3D printed aerospace parts that have been vapor fused.*

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## Test Plan

The test plan focuses on evaluating two of the most widely used materials in additive manufacturing for aerospace parts in North America. The objective is to assess their performance after a vapor smoothing process.

The first material is FR106, a flame-retardant polyamide (Nylon) 11. This material is favored in Selective Laser Sintering (SLS) for its superior ductility, impact resistance, and flame retardance. SLS is a powder bed fusion technology that involves using a heater to raise the temperature of fine plastic powder just below its melting point. A laser then traces the layer's cross-section to fuse the powder into parts. Then a new thin layer of powder is spread across the build platform, and the process begins again. As each new layer is added, existing material supports the structure, eliminating the need for additional supports during printing.

The second material explored in this study is ULTEM 9085 resin, a polyetherimide (PEI) based material known for its excellent heat properties & flammability up to UL94-V0. This material is used in Fused Deposition Modeling (FDM), one of the most popular additive manufacturing technologies in the industry. FDM parts are printed directly on a plate from a material extruding head on a layer-by-layer basis. This process is robust, allowing for the widest range of material usage of any additive technology.

Both materials underwent post processing through DyeMansion's VaporFuse Surfacing (VFS). Thermoplastic polymers consist of long polymer chains connected by hydrogen bonds and Van-der-Waals forces. During VFS, the polar solvent vapor condenses on the surface of the parts and dissolves these connections. This restructuring minimizes the surface area and surface energy, generating a smoother appearance. By removing the solvent from the parts using vacuum drying, the surface solidifies in its new, smoother form.

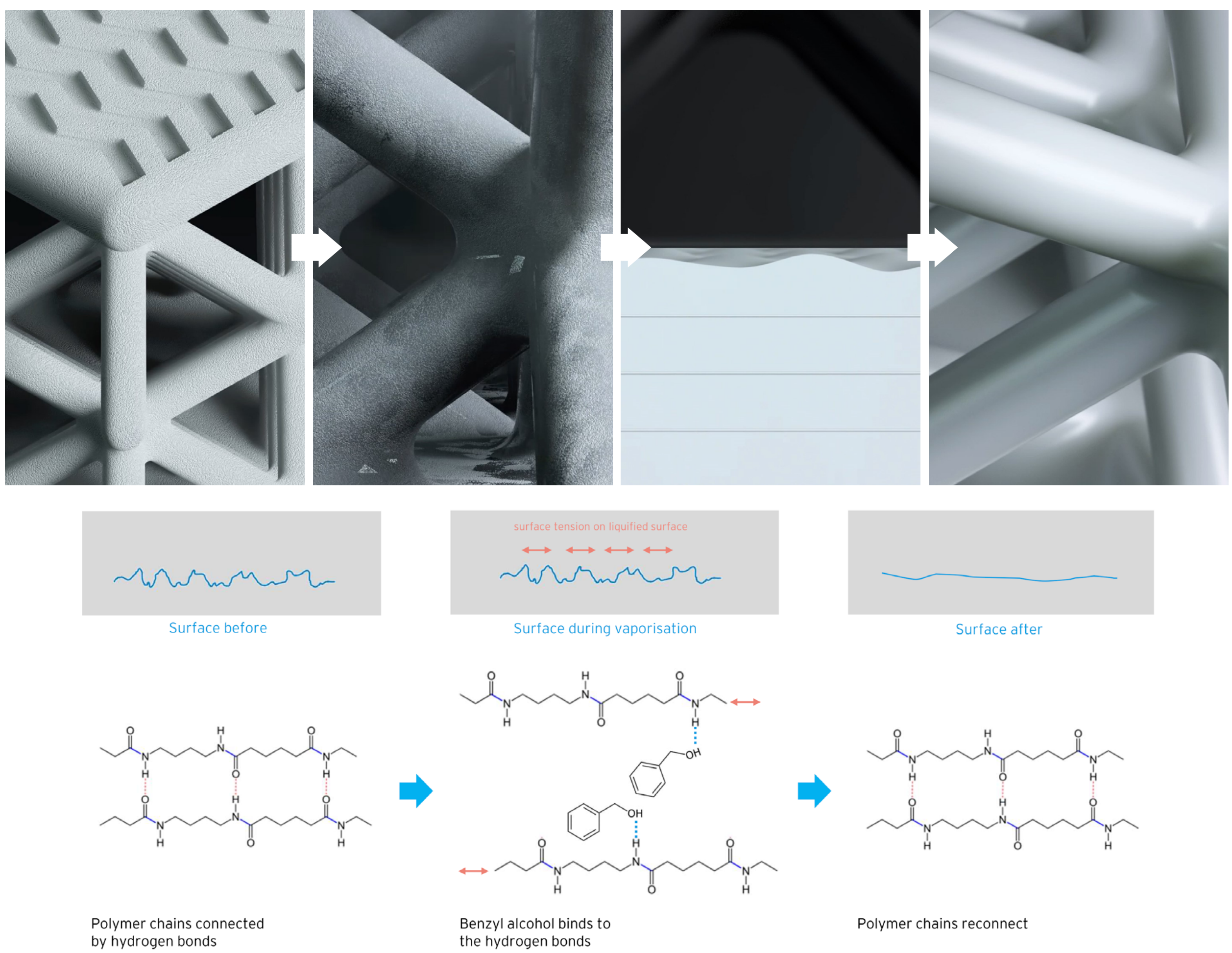



*Figure 1: Inside the Powerfuse S – how the process works*

Each material, ULTEM 9085 resin (FDM) and FR106 (SLS), had unique builds prepared to mimic how parts are produced during a normal 3D printing process.

Each build contained flammability strips at different orientations & thicknesses, 1mm and 2mm, tensile coupons in different orientations, dimensional coupons, and representative parts. The flammability strips were placed at different orientations and thicknesses because orientation affects performance. Thicker parts perform better in flammability testing because they have a lower surface area-to-volume ratio. As the parts' thickness increases, the additional material stabilizes against the flame. Orientation is an important characteristic of all additively manufactured components. There is anisotropy in properties based on orientation, which is most pronounced between the Z axis, where each new layer is printed on top of the previous. This layer-based boundary tends to be weaker than the intralayer strength.

One group of specimens was left as a control, and the other was tested after VFS. The criteria for measuring success are tensile properties, flammability (to Federal Aviation Regulations (FAR) 25.853), dimensional stability, part visuals, and surface roughness.

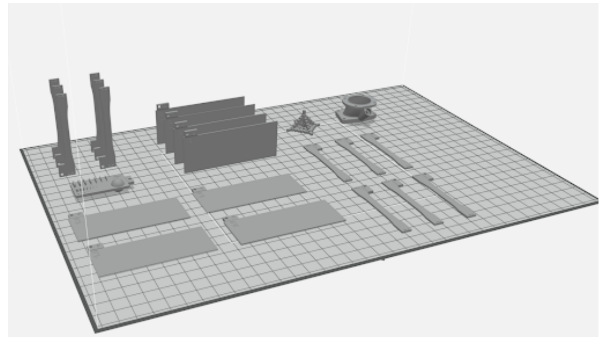


*Figure 2: FDM Test Build*

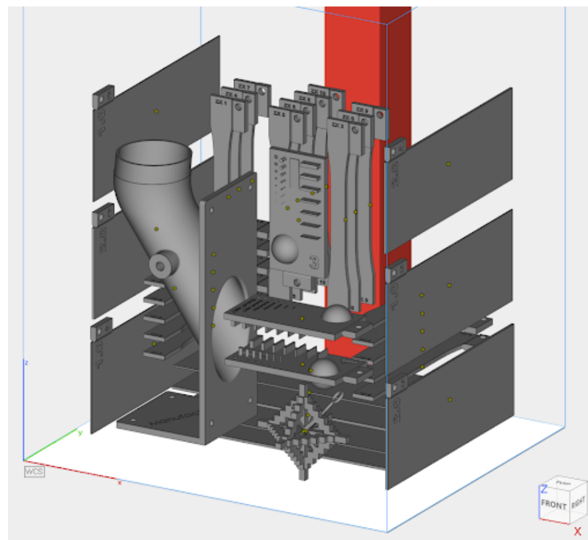


*Figure 3: SLS Test Build*

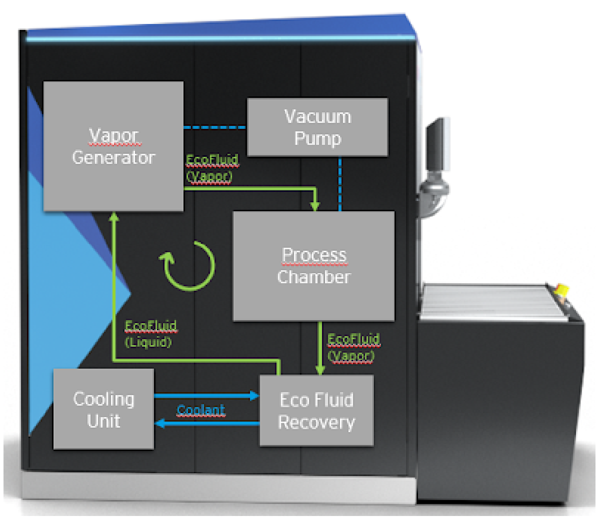



*Figure 4: VaporFuse Surfacing process flow*

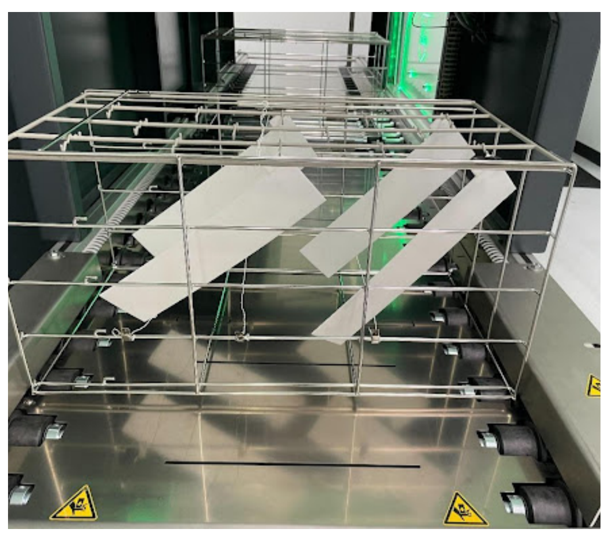


*Figure 5: Flam strips suspended in VaporFuse Surfacing processing basket*

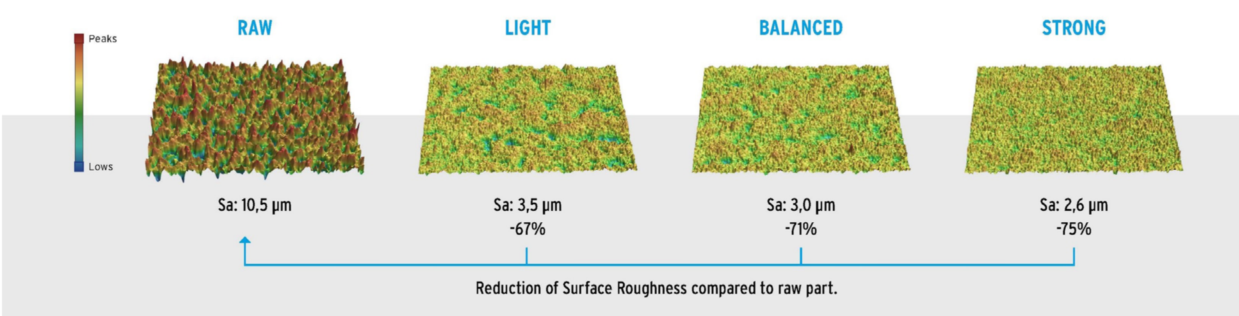
## A Deep Dive into VaporFuse Surfacing

When preparing a 3D printed part for VFS, there are a few general factors to consider: maximum part dimensions (300mm x 300mm x 300mm), a minimum wall thickness of 0.8mm, a minimum gap size of 1mm, rounded corners/edges versus sharp corners, and access to ducts or through-holes. Additionally, incorporating design features that ensure secure mounting and optimal hanging alignment is essential to minimize vapor buildup or run-off during processing.

The VFS process was chosen for this study because of its unique attributes over other post-processing surfacing systems. Unlike rival vapor smoothing systems, DyeMansion's VFS uses an environmentally, non-CMR solvent known as VF47 Eco Fluid (benzyl alcohol) which is managed within a closed loop process flow. This safeguards operators from solvent exposure and permits continuous vapor collection for re-use. Additionally, VFS allows for custom program development to tune for specific surface needs and offers 3 pre-programmed smoothing levels for standard materials: light, balanced, strong. The VFS is also configurable in an automatic loading mode which allows for 24/7 operation.

In contrast, vibratory tumbling is another method of post-processing surface treatment, but when compared to VFS, it is often more aggressive in its surface removal and less uniform throughout the part(s). Sharp edges are often rounded, small features are vulnerable to breakage and geometric tolerances are more likely to change.

Transitioning from raw printed parts to smooth parts requires minimal steps. While cleaning processes vary between FDM and SLS technologies, each has its own method of support or material removal. Once the parts reach an acceptable level of cleanliness, they are ready for the VFS process. For SLS parts, this entails media blasting the part after the print to eliminate any loose particles (remaining material or media). For FDM, this means manual support removal to retain only the ULTEM material.



Due to the evaporative nature of the Eco Fluid solvent, DyeMansion maintains the position that the consideration of mechanical property benefits should be approached with caution. These benefits may vary significantly if assessed immediately VFS or weeks to months later. To address this performance variability rising from residual solvent within parts, and to offer users a choice, DyeMansion has introduced an additional drying step within the process. While the VFS has a closed-loop recapture process for the solvent, some levels of trace solvent may remain in parts following the standard program cycle. By running the extended drying cycle, which can last up to 12 hours, the system can recapture as much solvent as possible. This allows parts to achieve the benefits of the vapor smoothing, while minimizing trace solvent for more predictable and consistent part properties. This extra step suits applications that require biocompatibility or resistance to flammability, for example.  While drying is not required to achieve certain levels of certifications, it can be leveraged to evaluate the impacts of dry conditioning vs processed, as-is.

The VFS process is a widely applicable technology for additively manufactured parts. While it facilitates the process adoption into several printing processes, materials and applications, it is important to note that some considerations may be necessary due to several contributing factors. For instance, when examining the testing of the FR106 and ULTEM 9085 resin materials from two different printing processes, ULTEM 9085 parts will see greater surface variability based on part orientation. This variation stems from differences in surface or build layer resolution between SLS and FDM which favors SLS in this case. Conversely, a cylinder built vertically in the Z direction within an FDM system will have nicely stacked layer lines that are more easily smoothed. A cylinder built horizontally in the XY direction, however, will have more noticeable stair stepping, particularly at the beginning and end layers of the part, and will be more difficult to smooth due the impact of the build layer thickness (the finer the build layer, the better the opportunity for smoothing). While the same orientation results are true for SLS, the much finer material grain size and layer resolution favor a more uniform smoothing result.

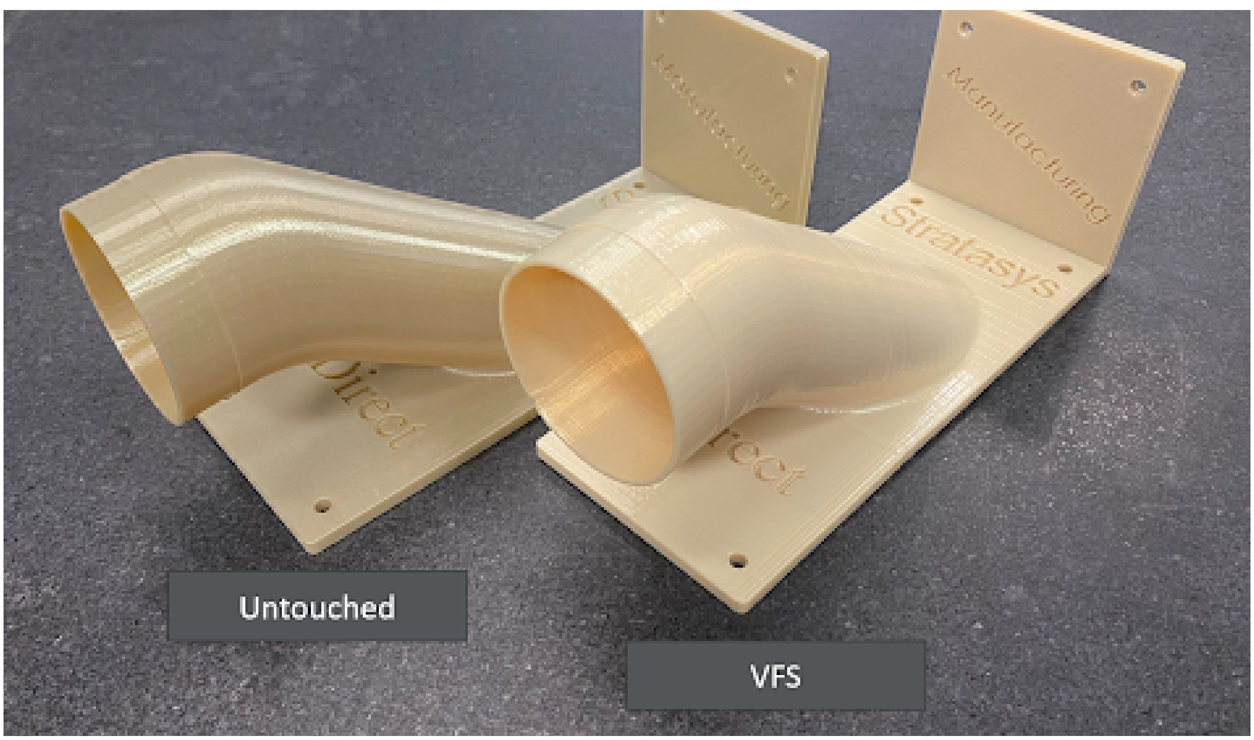



*Figure 6: Raw & VaporFuse Smoothed FDM Part*

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## Results – ULTEM 9085 Resin Comparison

The following results are broken down by the property that was being investigated for FDM ULTEM 9085 parts. Currently, the most popular finishing techniques for ULTEM 9085 are epoxy impregnation and prime and paint. Both help seal and smooth the surface but are a high-touch-time process.

### Surface Finish

Directly off the machine, ULTEM 9085 appears tan, with a semi-glossy finish with noticeable layer lines. Although they were built in the same material, the parts have noticeably different textures based on how the parts were oriented during the build: top surface, bottom surface, or across layer lines. Once the ULTEM 9085 parts had been smoothed, they achieve a glossier surface than a standard ULTEM 9085 part. The difference between raw ULTEM 9085 and VFS parts is more noticeable under a microscope. After VFS, parts have less noticeable layer lines because the surface liquifies and solidifies during processing, as shown in Figure 7. As the surface liquifies, it fills in depressions between rasters & layers. This minimizes the peaks on the surface to fill in the valleys, which reduces the surface roughness while decreasing the surface porosity.

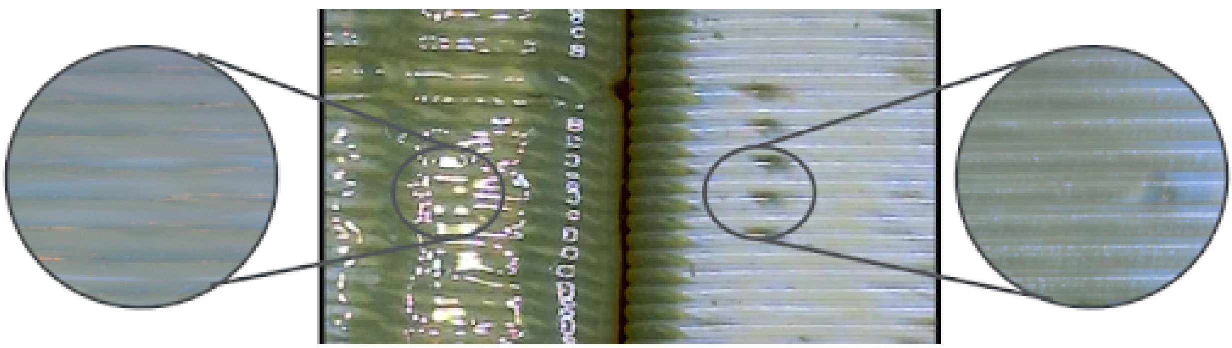

*Figure 7: Surface Finish Under Microscope - ULTEM 9085 resin (Left – VFS, Right – Raw)*

*Figure 8: Inside the Powerfuse S – how the process works*

The enhanced uniformity of the solidified surface on the parts is also quantifiably improved. In their raw state, the surface roughness is influenced by the print orientation. Once the parts had been smoothed, the roughness was between 500-600 micro-inches, regardless of how the part was printed. This is advantageous to designers concerned with achieving minimum callouts. After VFS, the surface roughness becomes independent of orientation. This is important when considering alternatives to VFS. Hand finishing is constrained to areas accessible to operators. If sandpaper cannot reach a specific area for sanding, altering the surface roughness becomes unfeasible. Tubes with a diameter under 4 inches are difficult to impossible to sand. Depending on the geometry, even shot-peening cannot improve the surface because the blasters need a line of sight to where the shot-peening needs to occur.

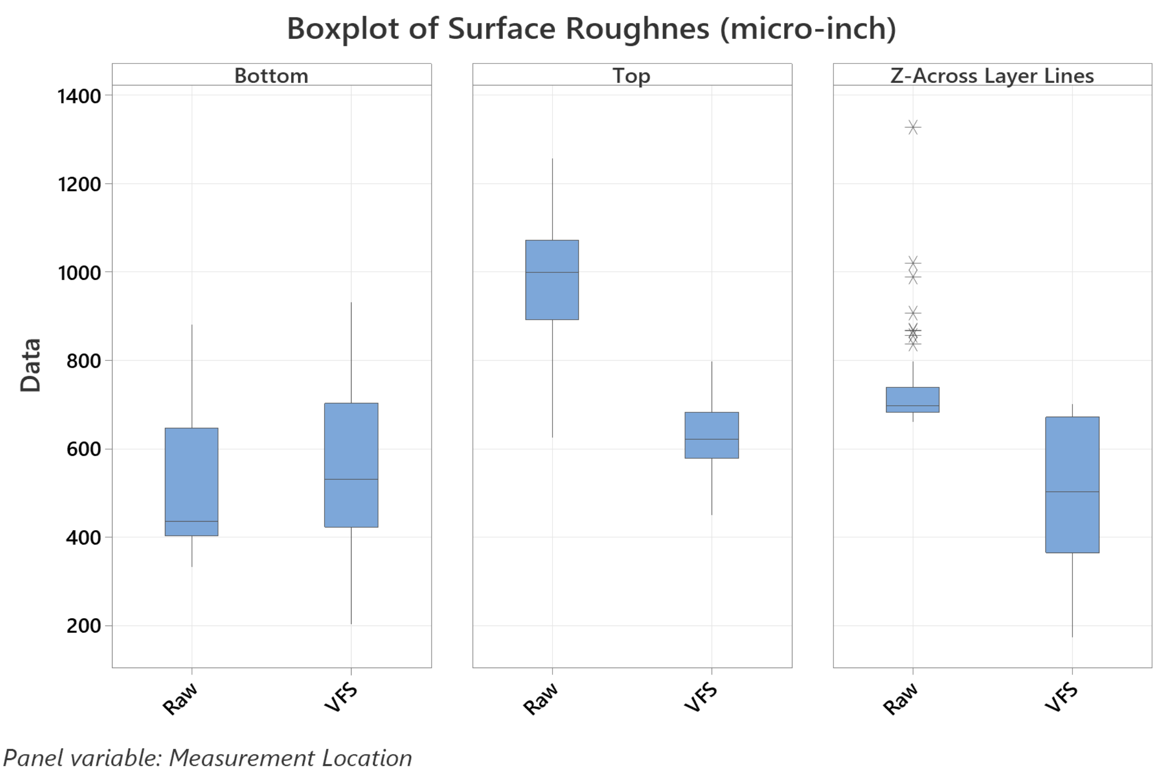


*Figure 9: ULTEM 9085 resin Surface Roughness*

## Tensile Properties

The tensile properties of FDM parts are influenced by their print orientation. Most designers create their part around the weakest axis Z. Figure 10-12 are separated by the print orientation for tensile strength, modulus, and elongation. After processing, there are no noticeable trends on mechanical properties. This benefits designers because they can use raw part properties, and can add VFS to improve sealing, visuals, and surface roughness without weakening the parts.

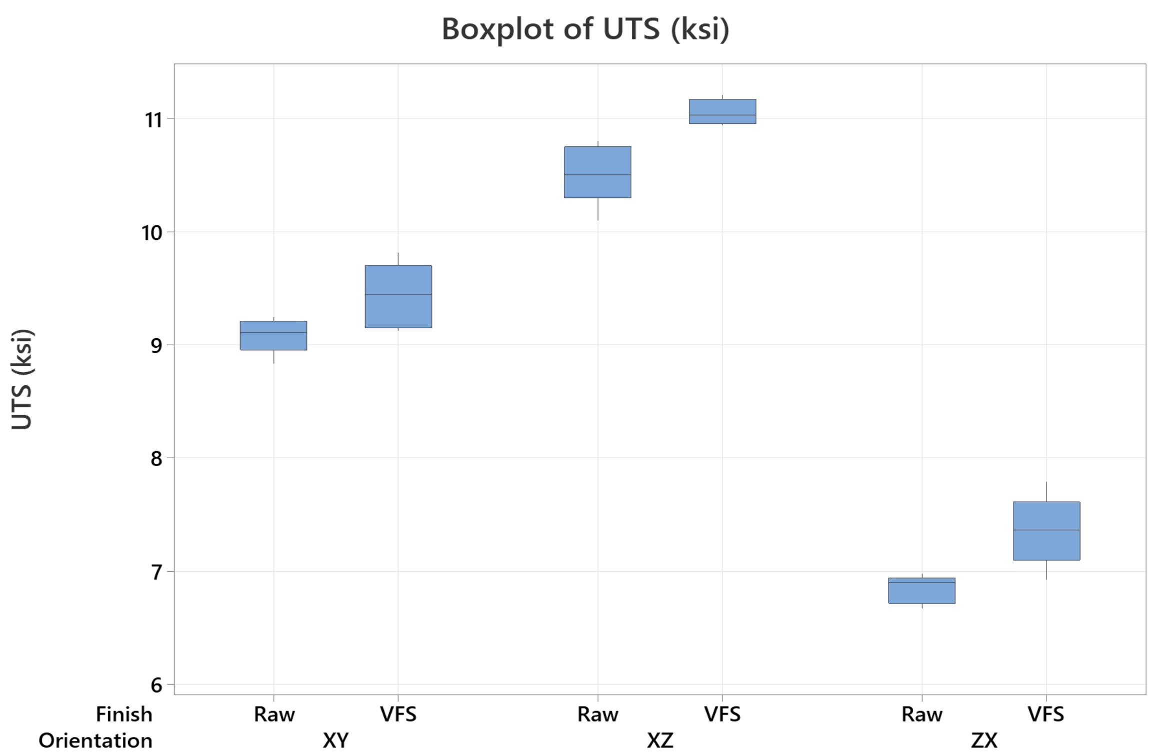


*Figure 10: ULTEM 9085 resin Ultimate Tensile Strength (ksi)*

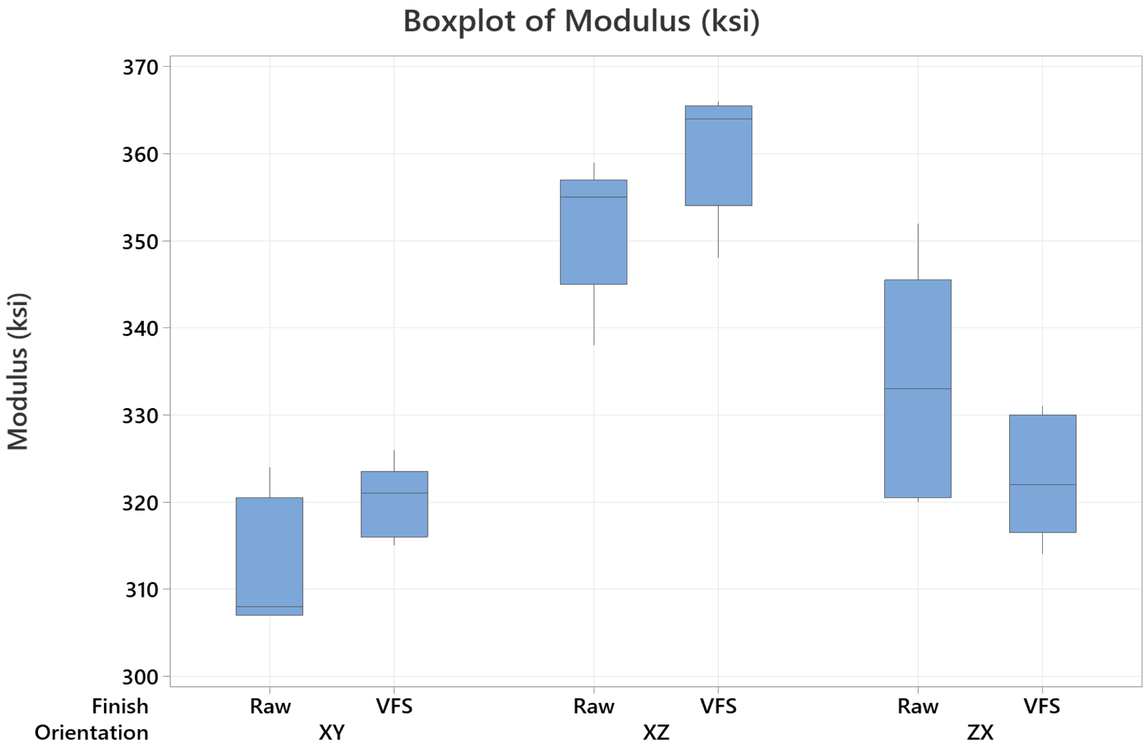


*Figure 11: ULTEM 9085 resin Young's Modulus (ksi)*

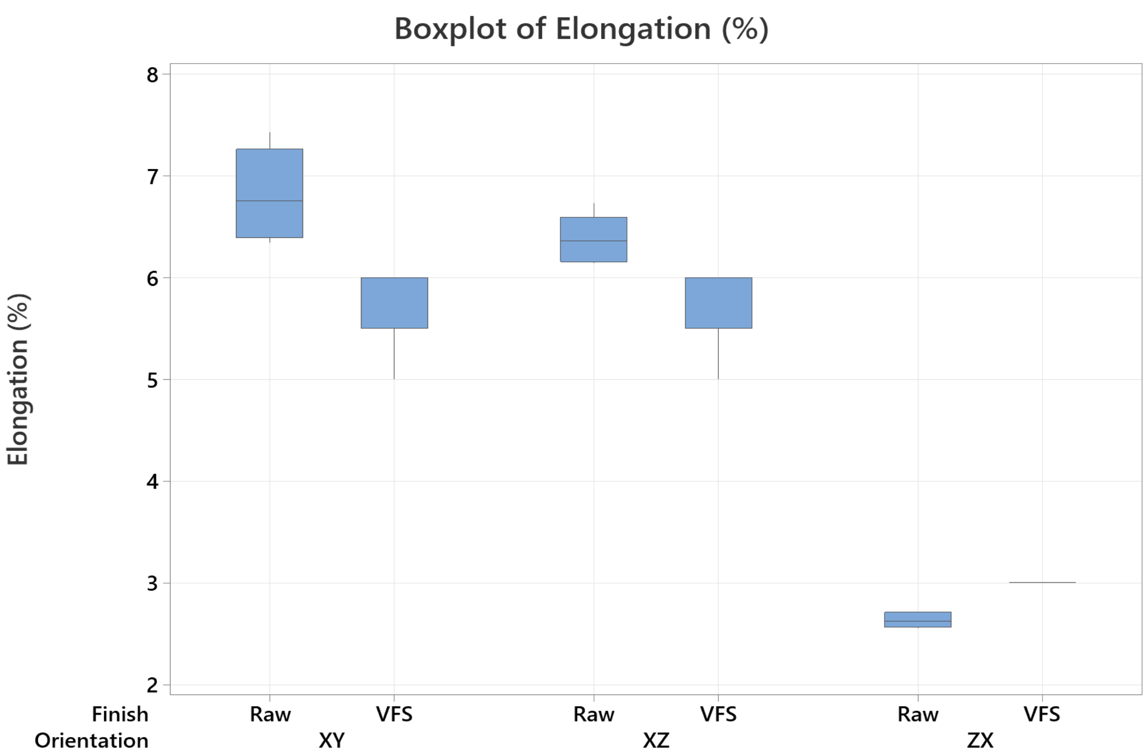


*Figure 12: ULTEM 9085 resin Elongation at Break (%)*

## Flammability

Testing flame strips to Federal Aviation Regulations (FAR) standards is vital for ensuring aircraft safety and compliance. These tests assess the flammability of aircraft interior parts. This test is regardless of the manufacturing method being traditional or additive. This test confirms that the parts in aircrafts will meet the safety requirements and mitigate fire hazards on planes. Compliance with FAR standards is crucial for aircraft certification, promoting the use of additive manufacturing in aerospace.

The flame strips were tested to Federal Aviation Regulations (FAR) standards for aircraft interior parts called 14 CFR 25.853. This test places the specimens in a vertical position and exposes them to 60 seconds of a flame. To pass the flammability portion of this specification, parts must have an average burn length less than 6 inches, the average flame time after removal of the flame source cannot exceed 15 seconds, and drips must self-extinguish for an average of 3 seconds after falling.

The parts tested were multiple orientations and thicknesses. In general, parts have better flammability properties the thicker the cross section & in the XY orientation. The study confirmed that thicker and XY-oriented 3D-printed parts have improved flammability properties – even after VFS. VaporFuse Surfacing had no effect on the flammability properties because 100% of the specimens tested passed. The parts exhibited non-drip behavior and immediately self-extinguished after the flame removal. The burn lengths can be seen in Figure 13. The smoothing process did not affect the flammability of Ultem 9085 parts and allowed it to be a viable material for critical aerospace applications while offering an efficient post-processing solution. It is important to note that ULTEM 9085 samples underwent VFS processing, incorporating an extended drying cycle to maximize the removal of trace solvent.

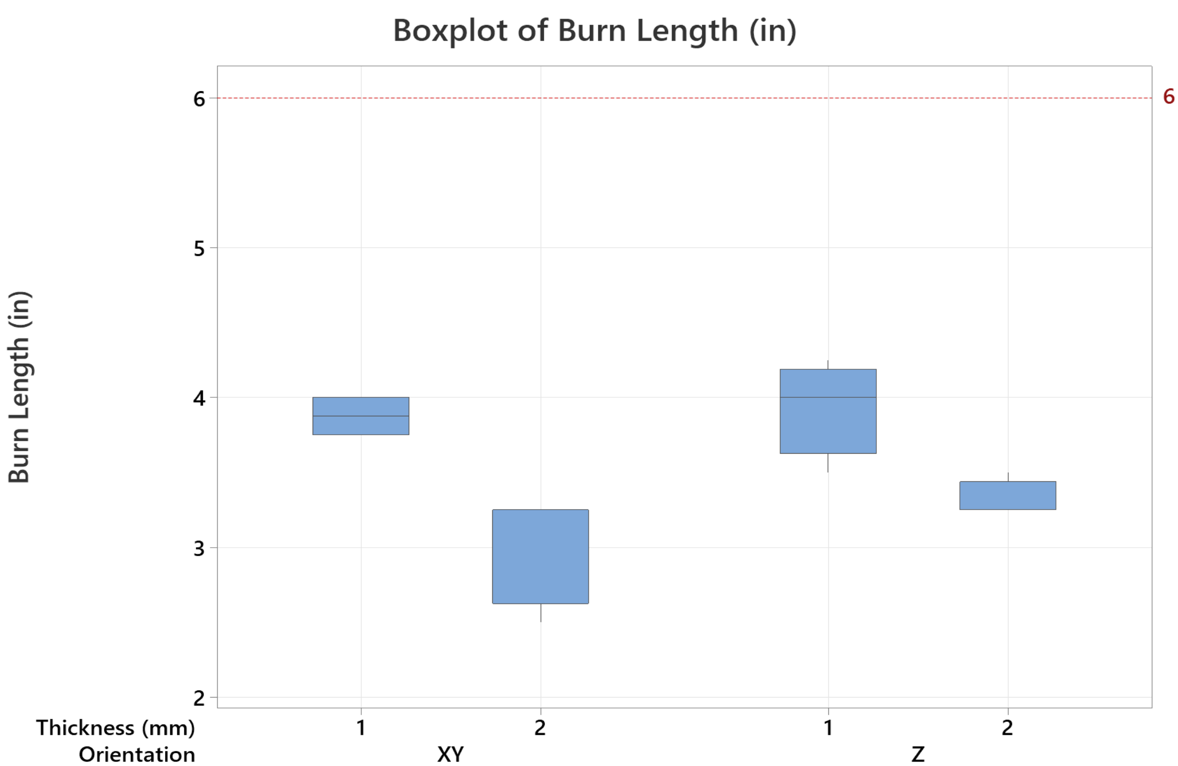


*Figure 13: ULTEM 9085 resin Burn Length by Orientation and Thickness*

## Results - FR106 Comparison

The following results are broken down by the property being investigated for SLS FR106 parts. Currently, the most popular finishing techniques for FR106 are manual sanding and prime and paint. After printing, FR106 has a rough-grainy surface, therefore sanding has become standard operation for this material. Sanding can improve the tactile experience by reducing surface roughness, but the visuals do not improve. In situations where visual criteria apply to FR106 components, the standard recommendation has been to consider priming and painting the parts.

## Surface Finish

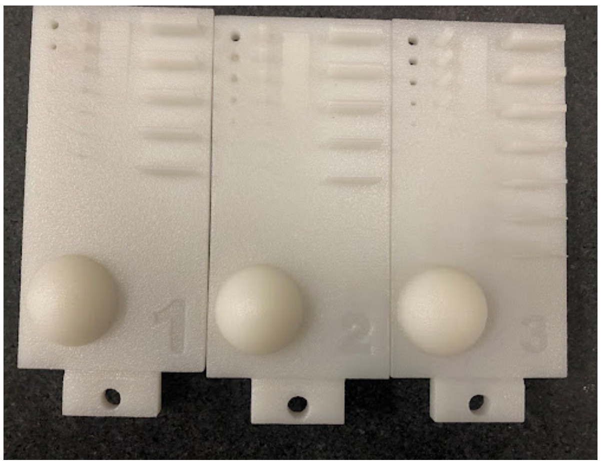

Figure 14: VFS Processed FR106 Parts

Following the VFS process, FR106 parts exhibited a significant visual improvement. The parts displayed a glossy surface, as demonstrated in Figure 14. The sugar cube-like surface finish that is characteristic of SLS-processed parts evolved into a texture similar to that of injection-molded components.

The surface changes were not purely cosmetic. Parts roughness also underwent a significant transformation. Both the bottom and top surfaces of parts saw an approximate ~65% reduction in surface roughness, reaching around 200 micro-inches Ra.

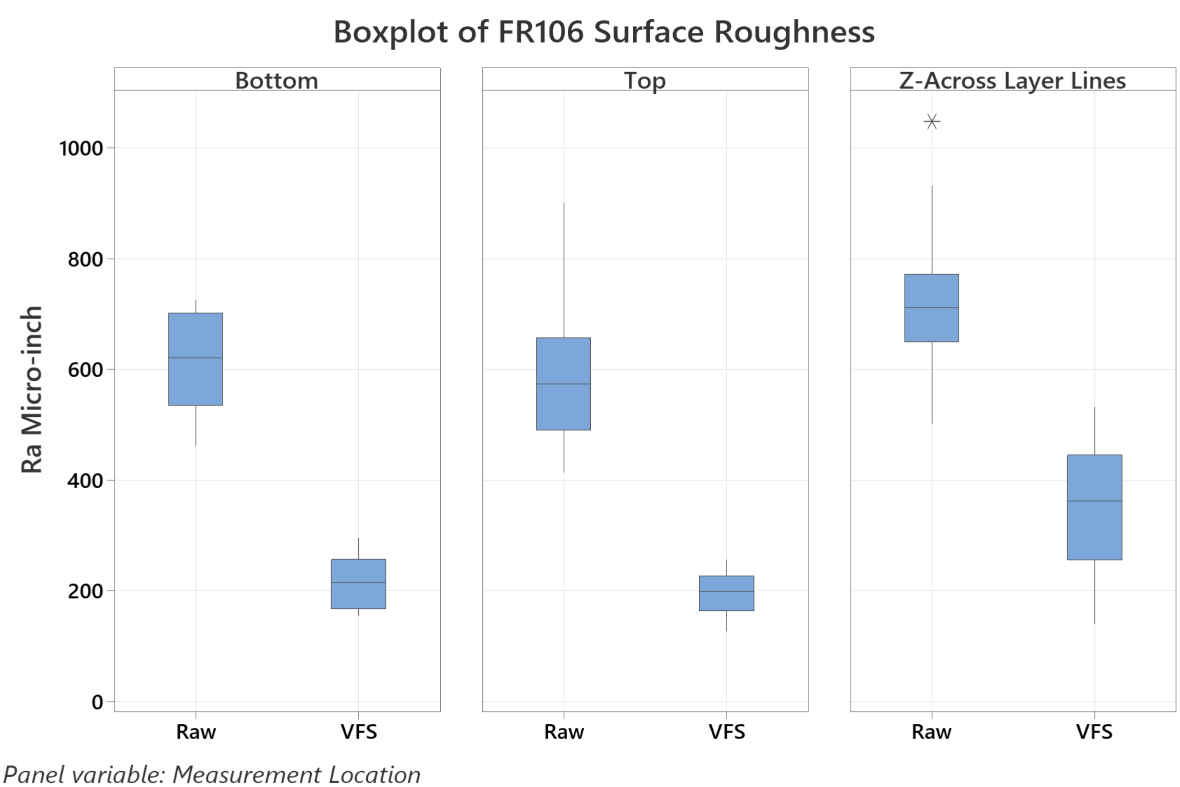


Figure 15: FR106 Surface Roughness

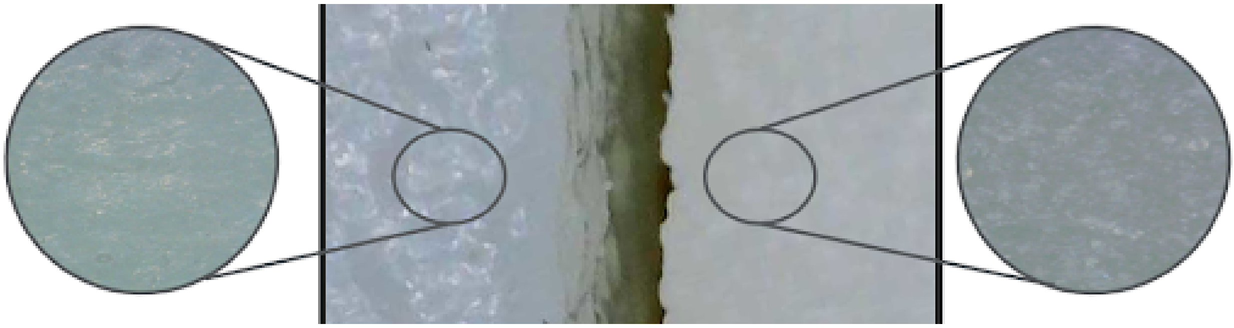

*Figure 16: Surface Finish Under Microscope - FR106 (Left – VFS, Right – Raw)*

Across layer lines, the decrease was ~50%, lowering the average Ra value from 728 micro-inches to 355 micro-inches. The single cycle time for Vapor Fuse Smoothing for these parts was 74 minutes for half a build of parts. This is a considerable time reduction compared to manual finishing. Furthermore, Vapor Fuse Smoothing can access areas that manual finishing cannot.

## Tensile Properties

The drying cycle for SLS parts wasn't as extensive as that for FDM. Unlike SLS, FDM parts underwent multiple iterations of the drying cycle. Parameters in VaporFuse Smoothing can be adjusted per material, allowing the choice between faster part processing and the number of drying cycles performed. As a result, some solvent remained absorbed in the final parts. This introduced a plasticizing effect, leading to increased elongation and decreased modulus. With further testing employing more aggressive drying cycles, the mechanical distinction became notably less pronounced. This is particularly evident in Figure 18, which depicts a reduced modulus, and Figure 19, which shows an elevated elongation.

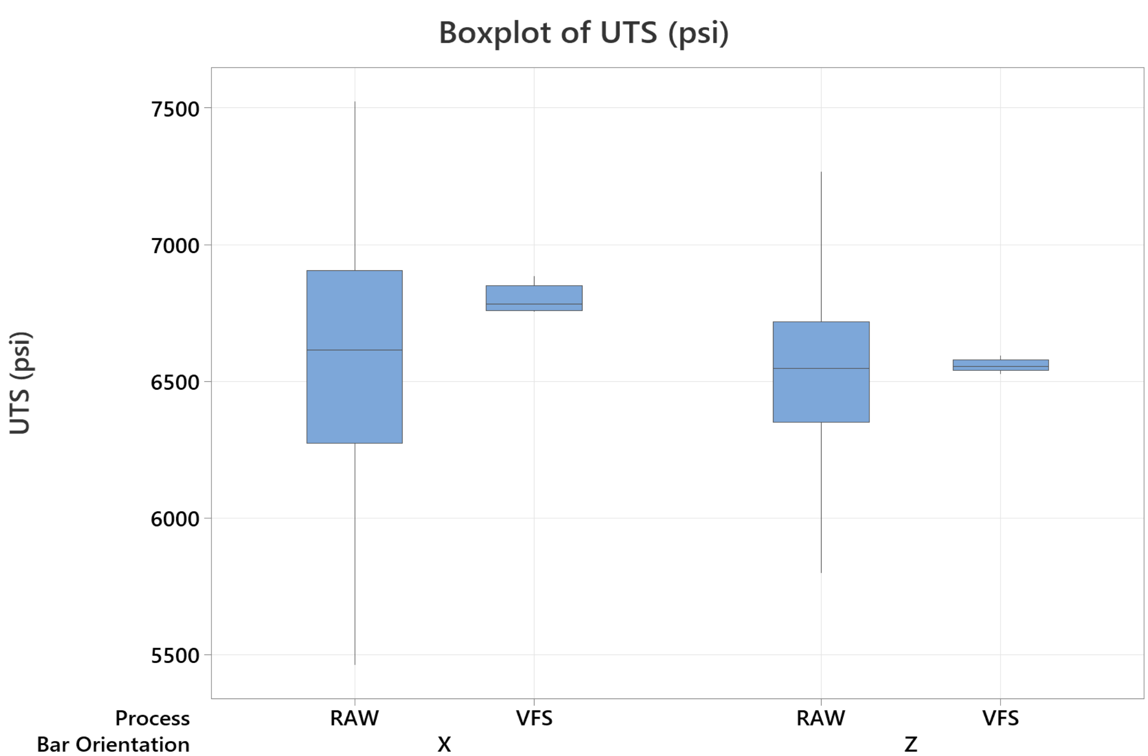


*Figure 17: FR106 Ultimate Tensile Strength (psi)*

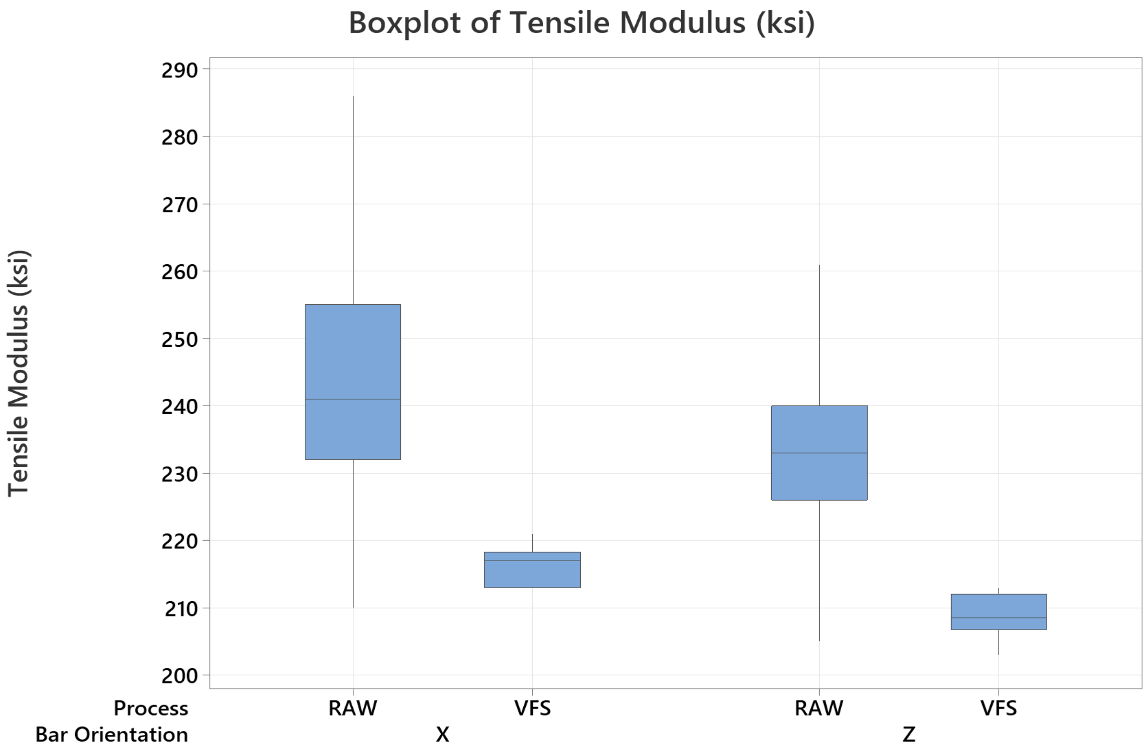


*Figure 18: FR106 Young's Modulus (ksi)*

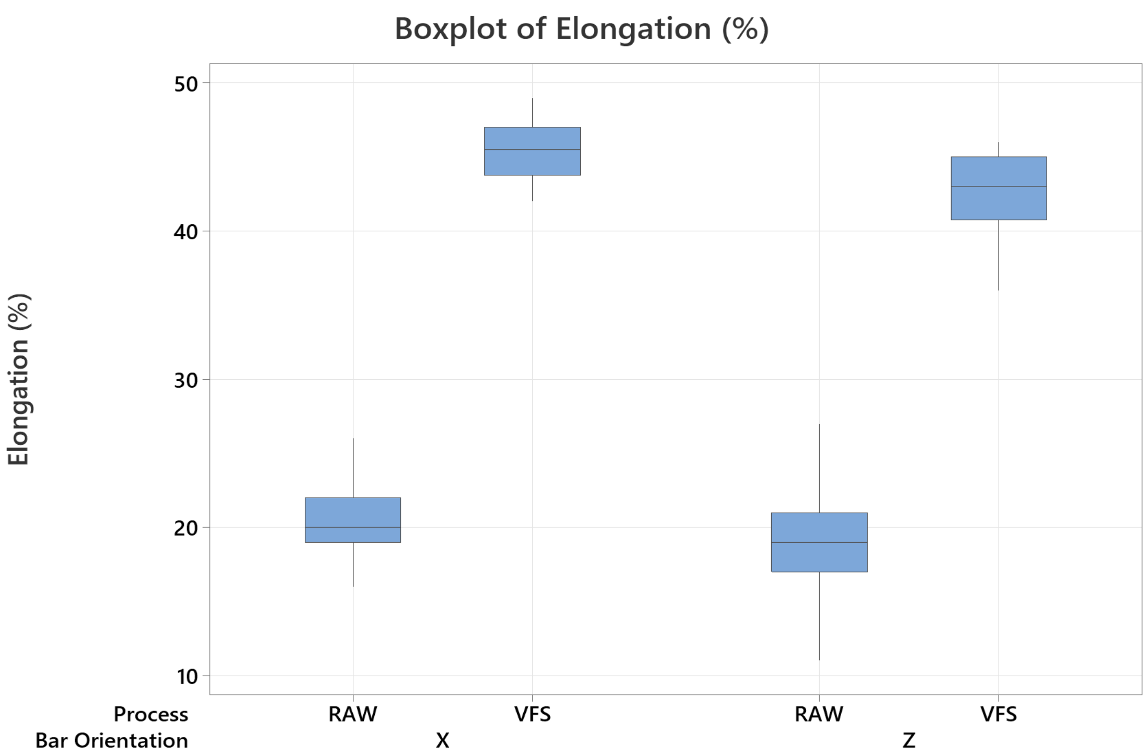


*Figure 19: FR106 Elongation at Break (%)*

### Flammability

To introduce the FR106 test, the parts were not treated to the additional drying cycle. With the solvent remnants not fully removed from the parts, it was observed that the solvent had a minor impact in flammability if compared to the as-printed sample. Its burn length was closer to the minimum passing level at an average burn length of 6 inches, but the parts still had a 100% passing rate. The average burn length for 1mm (about 0.04 in) thickness parts was 5.5 inches, and 4.2 inches for 2mm (about 0.08 in) thickness. As thickness increases the safety factor for passing the test also increases. If processing time were extended to enhance the drying cycle, solvent evaporation would similarly increase, further enhancing the safety factor in the test.

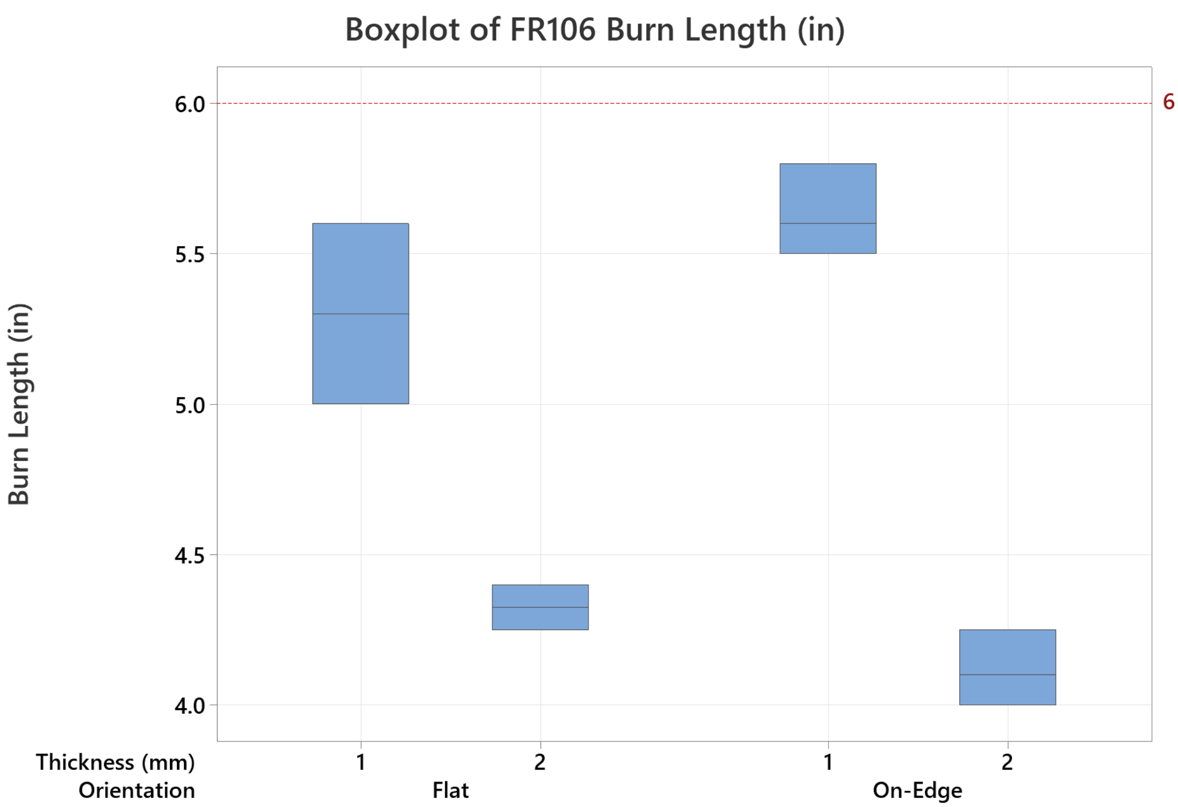


*Figure 20: FR106 Flammability Burn Length*

## Summary

In conclusion, this study demonstrated the significant impact that VaporFuse Surfacing (VFS) can have on enhancing the esthetics and performance of additively manufactured parts, specifically those made from ULTEM 9085 resin and SLS FR106 materials. Through careful analysis, we observed improvements in mechanical properties, flammability, dimensional stability, part visuals, and surface roughness after vapor smoothing treatment.

We discovered that when a maximum drying cycle is applied, the mechanical properties, flammability, and dimensional stability experience minimal changes, ensuring the structural integrity and safety of the parts. However, the most striking enhancements were in the visuals and surface roughness of the parts. Vapor smoothing allowed us to achieve a level of finish previously attainable only through manual finishing techniques, expanding the visibility of parts within the aircraft cabin.

Currently, companies rely on costly manual finishing techniques to achieve this finish, which limited the cost-effectiveness of many parts in an aircraft. By leveraging vapor smoothing, parts that were once hidden behind panels can now be displayed within the cabin without automatically being identified as a 3D printed part. Some examples could be seat end caps or portions of wall panels.


*Figure 21: Part Examples in Aircraft*

The other improvement is in the most common aircraft application space, environmental control systems. Fluid flow is affected by the roughness of the surface of the conduit it flows through. It loses energy due to the friction on the part. A higher surface roughness creates more friction, so a more efficient duct was made possible after the vapor smoothing process.

In separate tests, DyeMansion has observed an increase in vessel pressure holding capacity after VFS treatment. This additional sealing, regardless of the complexity of the duct allows for less of a pressure drop as the fluid travels through, resulting in improved energy efficiency and energy losses during operation.

DyeMansion's VaporFuse Surfacing introduces a practical and automated solution to replace traditionally labor-intensive hand-sanding or painting methods, especially when dealing with complex geometries that require uniform finishes. As parts become more complex and take full advantage of additives capabilities, having automated solutions like VFS will expand additive manufacturing's reach within the aerospace industry by improving part visuals and performance without significantly increasing the part cost.

## Conclusion

This study underscores Stratasys Direct's commitment to remaining at the forefront of additive manufacturing (AM) applications in the aerospace industry. As a leading additive manufacturing provider, Stratasys Direct pushes the boundaries of what is possible, striving to glean valuable insights that not only advance aerospace manufacturing but also hold potential applications across various other industries.

Through rigorous testing and analysis, we have demonstrated the transformative power of VaporFuse Surfacing (VFS) on 3D-printed parts made from ULTEM 9085 and SLS FR106 materials. The significant improvements in mechanical properties, flammability, dimensional stability, part visuals, and surface


*Figure 22: Airtightness after VFS treatment*

roughness achieved through VaporFuse Surfacing exemplify our dedication to optimizing AM solutions for aerospace applications.

By focusing on the esthetic and performance enhancements enabled by VaporFuse Surfacing, we have paved the way for more parts to be displayed within the aircraft cabin, breaking away from the limitations of costly manual finishing methods.

In addition, the observed advancements we discovered in sealing and surface roughness have far-reaching implications for the aerospace industry. The efficiency gains in environmental control systems due to reduced friction and energy losses offer the potential for significant cost savings and improved aircraft performance.

Stratasys Direct continually strives to unlock new applications in AM, with the goal of sharing and applying our findings to industries. The knowledge gleaned from this study will accomplish that goal, as it has the potential to revolutionize manufacturing practices across various sectors, translating into increased efficiency, cost-effectiveness, and enhanced aesthetics across multiple industries.

By harnessing the power of VaporFuse Surfacing and other cutting-edge technologies, Stratasys Direct affirms its commitment to redefining the boundaries of additive manufacturing. As we continue to pioneer advancements in aerospace and beyond, we aim to set new benchmarks for excellence and propel the entire industry towards a future of unparalleled possibilities.

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