Advanced Materials Testing Plan for the Space Suit Portable Life Support System

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The Space Suit Portable Life Support System (PLSS) has a tight mass requirement to meet while also meeting other requirements for supporting a crewmember in space, on the Moon, or on Mars. To meet these requirements, atypical materials must be considered to close the mass budget allocations. However, many of these materials and processes are relatively new and untested. Therefore, initial analysis and testing of some new and advanced processes have been conducted following a roadmap presented last year. This material testing has focused primarily on thermoplastics, both additively manufactured and machined, to assess plating and fastening operations that will be required. These processes will provide additional strength and shielding capability typically only achieved with metallics. This testing has also helped to define a forward plan to certify these materials and processes for critical spaceflight applications. This report will review testing plated thermoplastics both for strength and thermal properties. It will also review fastener and fastening options and look at insert and fastener testing. It will also review state-of-the-art methods being considered elsewhere and some additional testing being conducted. Using the testing results researched here, there will be recommendations on applications for each of these types of methods going forward.

Nomenclature

ABS	=	Acrylonitrile Butadiene Styrene
AM	=	Additive Manufacturing [4]
CF	=	Carbon Fiber
DCU	=	Display and Control Unit
EBM	=	Electron Beam Melting
EMI	=	Electromagnetic Interference
EMU	=	Extravehicular Mobility Unit
FDM	=	Fused Deposition Modeling
FOD	=	Foreign Object Debris
GF	=	Glass filled
HUT	=	Hard Upper Torso
JSC	=	Johnson Space Center
lb/in^3	=	Pounds per cubic inch (density)
MAPTIS	=	Materials and Processes Technical Information System
PBF	=	Powder Bed Fusion
PEEK	=	Polyetheretherketone
PEI	=	Polyetherimide
PLSS	=	Portable Life Support System
PGS	=	Pressure Garment System
RCA	=	Rapid Cycle Amine
SERFE	=	SWME EXPRESS Rack Flight Experiment
SLA	=	Stereolithography
SLS	=	Selective Laser Sintering
TRL	=	Technology Readiness Level
UTS	=	Ultimate Tensile Strength
xEMU	=	Exploration Extravehicular Mobility Unit (next generation)

I. Introduction

A. Overview

Advanced materials are important to reducing weight and maintaining capability for the space suit across all mission profiles. To utilize these advanced materials in spaceflight, material property testing for the extremes of spaceflight environment and specific applications are required for infusion into the design. This report identifies many advanced materials for consideration for infusion into the Portable Life Support System (PLSS) and provides a recommended flow path for infusing new materials. Materials such as high-performance glass filled or carbon filled machined thermoplastics are considered for infusion. Additive Manufacturing (AM), both for these new materials, as well as metals, are also considered for infusion. Furthermore, augmentation such as plating could be used to help improve strength properties of thermoplastics while keeping the overall material composition lightweight. Lastly, inserts are expected to meet requirements for bolt pull out strength but require testing and verification. This test series is being developed to help raise the overall Technology Readiness Level (TRL) for the advanced materials being considered.

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[4] Industry commonly refers to AM as 3D printing.

B. Suit Mass Reduction

The mass of the current Exploration Extravehicular Mobility Unit (xEMU), NASA's government-reference design space suit, is 391 lbs (177 kg) including both the PLSS and the Pressure Garment System (PGS), while an initial estimate for a Mars suit mass maximum is 229lbs (104kg) [2]. This would require a 44% reduction in mass from the existing government reference design. Furthermore, a current design effort with NASA commercial partners to build a suit for the lunar surface may benefit from weight reduction for the Artemis mission. This mass limit has previously been achieved during the Apollo missions, with the Apollo space suit at 194lb (89 kg) [2]. Apollo missions prioritized mass, only had short term stays, and had a higher risk tolerance, allowing factors such as single fault tolerance instead of two fault tolerance common with xEMU [2].

Rather than reducing EVA time or fault tolerance of the suit, weight relief could be obtained by using new materials and processes in existing systems. A previous report suggests for a set of chosen components, a replacement with thermoplastics alone could reduce mass up to 35 lbs in the xEMU PLSS [1]. However, many of these materials may be immature for spaceflight and may require additional testing. This report aims to review initial testing data, and outline plans to increase the maturity of the materials and processes proposed. These materials and processes may be infused directly into the design process to reduce mass of the suit.

C. Environment Considerations

To build confidence in the use of thermoplastics in spaceflight it is important to understand the environmental considerations for the application. Considerations include material properties such as ultimate tensile strength (UTS) and other mechanical properties, galvanic compatibility, thermal properties including operation at cryogenic temperatures, heat dissipation, electromagnetic interference (EMI) protection and grounding, oxygen compatibility, off gassing, and vacuum outgassing [1]. It is also important to ensure maintainability and overall service life of each component on the PLSS. For each application, the properties required must be selected appropriately. However, for many thermoplastics there are still many key missing properties. While basic strength, mechanical, thermal properties are typically published by the manufacturer, many important considerations for spaceflight may not yet be published or collected in one place. Water absorption and subsequent strength tests, oxygen index, vacuum stability, ultraviolet (UV) sensitivity, creep, and brittleness at cold/cryogenic temperatures are some important properties that are less common to find published. For applicable locations, these properties will need to be tested prior to integration.

D. Usage and Safety in Spaceflight

For space suits, most components are classified as criticality 1 where a failure could result in loss of life as defined in EHP-10101 "Failure Modes and Effects Analysis/Critical Items List (FMEA/CIL) Requirements." While machined thermoplastics are typically understood well enough that they could be used in applications where requirements match properties available, AM thermoplastics are typically considered not mature enough for use in critical systems. NASA-STD-6030 "Additive Manufacturing Requirements for Spaceflight Systems" does not allow for AM thermoplastics in their Class A level parts that are criticality 1 level parts [3]. Metallic AM could still be considered for Class A/Crit 1 parts, though thermoplastic AM may only be considered for Class B/C or Crit 2/3 failures. As thermoplastic AM is more understood and becomes more mature, it is expected that it may be readily available for use in Crit 1/Class A applications. For applications where a material/process could be used, NASA-STD-5001 "Structural Design and Test Factors of Safety for Spaceflight Hardware" requires a safety factor of 3 for all components providing safety of an astronaut for any materials. It is also important to ensure any components chosen to meet the fracture control plan outlined in NASA-STD-5019 "Fracture Control Requirements for Spaceflight Hardware." and the materials and process requirements in NASA-STD-6016 "Stand Materials and Processes Requirements for Spacecraft".

II. Advanced Materials

A. Material Options

Table 1 illustrates a recommended set of materials for consideration in critical applications. While there may be many more available, this list is intended as a place to start for comparing technologies. Of the materials listed, there are either AM or machined materials. Of the AM materials there are either Powder Bed Fusion (PBF)[5] for metals, Selective Laser Sintering (SLS) for thermoplastics and composites, and lastly Fused Deposition Modeling (FDM) and Stereolithography (SLA) for thermoplastics. These materials are also subcategorized by either plastic or metallic. These materials are ordered by their strength-to-density ratio as a first stop resource for selecting the best one for a particular application. However, this is a preliminary list. Many materials may be lightweight, but other properties make them unusable or increase overall weight in other ways such as brittle properties in thermal extremes [1]. Additive manufacturing also needs to evaluate anisotropy of the part due to the print method providing different properties depending on the axis. The best option is typically the highest on the list that meets all the other considerations and requirements for a component.

For AM thermoplastics, FDM is a more readily available option, although it has a lower general UTS than SLS and provides opportunities for more flaws and failure mechanisms that can be difficult to inspect such as voids in the print. Stereolithography (SLA) is also an option for AM using laser and liquid layers to create a part with precision results, although its strength to density ratio is very low in comparison to SLS considered in Table 1.

[5] Direct Metal Laser Sintering (DMLS) for metals and SLS for thermoplastics are types of PBF and may also be referred to PBF or vice-versa in industry.

Table 1. Advanced Material Options for Consideration

Material	Material Category	Process	UTS/ Density Ratio ksi/(lb/in^3) (MPa/(g/cm^3))	Density Average lb/in^3 (g/cm^3)	UTS ksi (MPa)
Titanium 6Al-4V [1]	Metal	Machine	969 (241)	0.16 (4.43)	155 (1069)
EOS Titanium Ti64 [5]	Metal	PBF (AM)	956 (238)	0.16 (4.43)	153 (1055)
Aluminum 7075-T73 [1]	Metal	Machine	713 (168)	0.101 (2.8)	68 (469)
EOS Aluminum AlSi10Mg [6]	Metal	PBF (AM)	673 (168)	0.098 (2.71)	66 (455)
PEEK 30% CF [30]	Plastic	Machine	529 (132)	0.051 (1.41)	27 (186)
PEI 30% GF (Ultem 2300) [18]	Plastic	Machine	466 (116)	0.0545 (1.51)	25.4 (175)
Aluminum 6061-T651 [1]	Metal	Machine	429 (107)	0.098 (2.71)	42 (290)
PEEK 30% GF [30]	Plastic	Machine	407 (101)	0.054 (1.49)	22 (152)
PEI (Ultem 1000) [19]	Plastic	Machine	359 (89)	0.046 (1.27)	16.5 (114)
PEEK [7]	Plastic	Machine	340 (85)	0.047 (1.3)	16 (110)
Nylon 12 + CF / Windform XT 2.0 [1]	Plastic	SLS (AM)	307 (76)	0.0394 (1.09)	12.1 (83)
Nylon 11 + CF / Windform SP [1]	Plastic	SLS (AM)	274 (68)	0.04 (1.11)	11 (76)
Polycarbonate 20% GF [1]	Plastic	Machine	268 (67)	0.0487 (1.35)	13.1 (90)
Vespel SP-1 [1]	Plastic	Machine	242 (60)	0.0517 (1.43)	12.5 (86)
Ultem 9085 [1]	Plastic	FDM (AM)	180 (44)	0.0483 (1.34)	8.6 (59)
DuraForm PA / Nylon 12 [8]	Plastic	SLS (AM)	171 (43)	0.0361 (1)	6.2 (43)
PerFORM [28]	Plastic	SLA (AM)	161 (40)	0.0582 (1.61)	9.4 (65)

B. Current Applications

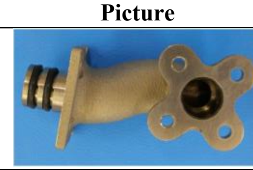
Table 2 shows a list of advanced material applications that have been integrated in recent years. The current TRL is reported in the table and ranges from 1 to 9 with 1 being basic principles studied and 9 being a used-in-flight proven design. For AM and thermoplastics, the TRL in space suit design is highly variable and depends on the component and application or environment being considered. The TRL is assessed based on the relevant application of the reference.

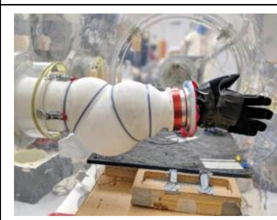
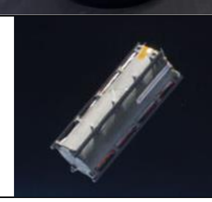
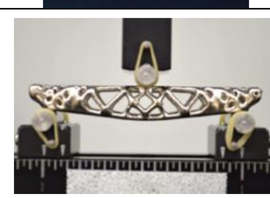
New research in Table 2 has focused significantly on AM. AM is a relatively new method with new properties to consider, but failure mechanisms that must be tested and certified for any material/process chosen. Extensive testing to explore these properties and failure modes will improve the maturity in spaceflight application to allow it in critical locations. Additionally, there are multiple instances of AM being used in pressurized locations. A common theme has been that post process machining is required for sealing surfaces, threaded features, or any other features requiring tight tolerances. Based on this experience, it is recommended to always post machine critical features on AM parts.

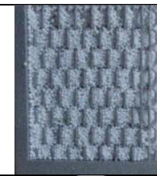
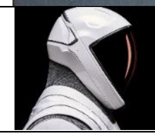
Machined thermoplastics on the other hand may be more prevalent for longer; however, the certification in spaceflight has been limited. There has been a lot of research in integrating thermoplastics and composites into aircraft [24]. There is also significant research into metal AM for spaceflight as shown in Table 2, and it does not require maturation for use like thermoplastic AM in NASA-STD-6030. There have been vendors that have flown thermoplastic AM in critical locations such as SpaceX helmet [3]. For instance, there has been one flight project, the SWME EXPRESS Rack Flight Experiment (SERFE), in recent years that has raised the TRL of metal AM and advanced metal processing techniques in space suit to 7 [9]. Therefore, both machined thermoplastics and metal AM could be considered at this time for potential infusion into critical spaceflight hardware such as the space suit.

To meet NASA-STD-5019, extensive testing and data is required; without testing, machined metals are typically chosen as default. In most cases presented below, the development of new materials has reached about TRL 4 but has yet to be integrated into the larger space suit subassembly that would be required to raise the TRL. However, currently there is only one xEMU PLSS unit in existence being worked and it is heavily controlled, requiring high fidelity for new component integration. This can make it difficult to integrate new components and raise TRL. Extensive component level testing and certification may be required prior to integration to build confidence to integrate into the xEMU or another future suit.

Table 2. Application of Advanced Materials for the Suit

TRL	Source	Description	Picture
7	NASA JSC [9]	SERFE flew to test a next generation thermal loop for the space suit. It included a prototype pump that utilized AM titanium with post process machining. This system was tested at vacuum on the ISS and functioned adequately.	

7	NASA JSC [1],[9]	This backplate was developed by NASA JSC with Langley research center using traditional machining methods but augmented with generative design for mass removal and Electron Beam Welded (EBM) Channels. Generative design has simplified the design iteration process to come to an optimized solution using automated systems and then verified using traditional methods. The EBM channels have helped reduce complexity by creating a single monolithic part. Additionally, a version of this method was also used and flown on the SERFE project in the vacuum of space and functioned without issue.	
5	NASA JSC [1],[10]	Ultem 9085 has been implemented in the Display and Control Unit (DCU) housing for the space suit government reference design. This was tested in the "Suit 2," a full PGS build, during thermal vacuum testing. It performed without any issues. Another prototype of the DCU housing was explored using Windform SP that was plated with nickel as a proof of concept shown here.	
3	Makel Eng. [11]	A multi-gas sensor primarily intended to measure carbon dioxide is being developed for NASA by Makel Engineering. Makel has explored metal AM as a method to create complex internal geometries for the sensor. They looked at mechanical and electrical polishing the sensor to improve the finish and sealing at first, though they are now looking at machining post processing to improve sealing surfaces.	
4	Hamilton Sundstrand [12]	A prototype AM heat exchanger for the space suit PLSS was fabricated out of titanium and Inconel using PBF. The sealing surfaces were machined before testing and the heat exchanger functioned adequately. It even had a bit higher effectiveness of heat transfer, thought to be due to the increased surface roughness. This demonstration shows the viability of using PBF in the space suit for complex articles such as these.	
3	University of Maryland [13]	An AM elbow assembly from the University of Maryland made from DuraForm PA has been tested at 4.3 psia relative pressure differential. It tested well overall, but there were leaks at the seals. They explored epoxy coating and sanding to improve sealing, but that did not work. Future work is to address some leaks due to surface roughness and to investigate traditional machining for post processing to improve sealing.	
3	David Clark [14]	Prototype AM for PGS solid portions has been studied by David Clark Company focusing on boots and helmets. These demonstrations indicate the ability for AM to meet the complex shapes needed for the PGS and can meet basic functional requirements through mechanical testing. The research notes this could be expanded to the large Hard Upper Torso (HUT) assembly, though indicates the need for continued materials testing.	
9	CRP/ Windform, G.A.U.S.S. Srl, Tetonsys, and others [15]	A Tubesat-POD was developed to launch cube satellites from the ISS. It utilized Windform XT 2.0 as the primary external structure. Two Tubesats were launched with this: Tancredo-1 and OSNSAT. While this is not space suit related, this demonstrates the ability of AM thermoplastics to successfully function for critical deployments in space.	
4	Repliform, Pennsylvania State & Formlabs [16]	Repliform in conjunction with Pennsylvania state has been exploring a method of plating AM with a copper/nickel coating to increase the strength of the overall structure. This method uses topology optimization combined with SLA AM to create complex forms, then plated and tested in bending with good results that rival AM PBF aluminum. Future work is needed to develop predictive models using this method and integrate it into hardware.	

4	Reaction Systems [27]	Reaction Systems has been exploring a method to create a lattice for the Rapid Cycle Amine (RCA) swing bed using AM. The figure shows a cross section of the amine beads in the AM lattice.	
9	SpaceX [3]	SpaceX conducted their Polaris Dawn mission with their suits that used polycarbonate AM as the base material for their helmet.	

III. Testing Plan

A. Testing and Infusion Process

To raise the TRL of components with advanced materials a process must be outlined for identification, testing, and infusion. A recommended infusion path is shown in Figure 1. First a set of components or applications must be identified along with the associated environment (vacuum, pressurized, water, oxygen, etc.). Then, based on the requirements, advanced materials should be chosen from the list above. A thorough review of all material properties should then be conducted to determine if the new material meets all the requirements for the environment and application including galvanic compatibility with adjacent materials. The Materials and Processes Technical Information System (MAPTIS) database can be utilized along with vendor data to determine if the material is sufficient. It is noted that vendor data should be verified for any critical parameters. If there is any missing data, then the part should be tested with an applicable testing method to gather missing data. The previous materials report outlines a list of standard tests that could be completed to test and certify material properties [1]. If the properties are sufficient, a prototype should be designed, analyzed and tested.

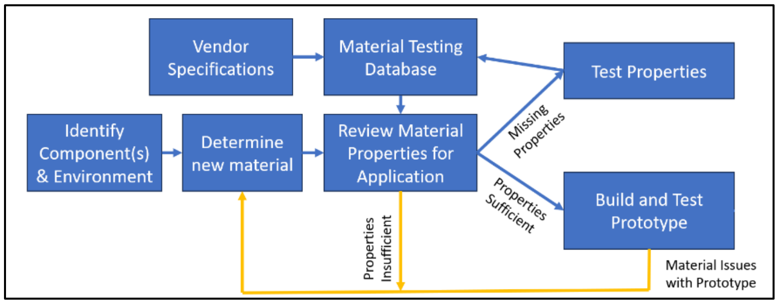


Figure 1. Material infusion process diagram

For infusion of thermoplastics, there is still a large gap of testing in machined thermoplastics. Therefore, certification and infusion of machined thermoplastics should be evaluated first prior to evaluating AM thermoplastics.

B. Applications in the PLSS

The first step is understanding the components on the PLSS and where advanced materials can be added. The PLSS is made up of a ventilation system, thermal loop system, avionics and power system, and structure. High pressure oxygen supply loops are not considered in this report due to the complexity of material choices required for compatibility with high pressure oxygen. All different systems could infuse advanced materials but have different requirements. They are broken out below:

1. Ventilation System

The ventilation system consists of manifolds, fans, CO_2 removal systems and associated housings, and heat exchangers. Advanced materials such as thermoplastics could be integrated to replace the bounding pressure-holding elements. There is only 10.6psid maximum differential pressure (MDP) such that the stresses would be relatively low. The materials selected would need to pay special attention to the 100% oxygen requirement and select fire resistant options or conduct an Oxygen Compatibility Analysis (OCA) to determine the ignition risks, if any.

2. Thermal Loop System

The thermal loop systems consist of pumps, housings, water evaporator, heat exchanger, check valves, and associated tubing. Advanced materials could be used to replace any non-active pressure holding elements in the water loop. The water loop is relatively low pressure so stress should be small. Special attention and testing should be conducted to verify the iodinated water is compatible with the material chosen and the material does not leach into the water loop. Furthermore, galvanic compatibility should be considered when coupling the component to a dissimilar material.

3. Avionics and Power

The avionics and power system consists of multiple avionics boxes and battery housings. The enclosures and housings could be replaced with advanced materials as they do not hold a lot of stress. Special attention should be paid to EMI, thermal, and bonding requirements. The avionics boxes need to protect the electronics from electrostatic discharge, and the board produces some heat that must be sunk to avoid overheating.

4. Structure

Structure includes any materials used to hold all the other components of the PLSS together. The primary structural elements may require need to be metal for strength, however, there are many brackets that could be switched to advanced materials. The backplate could consider lighter weight metals like aluminum, or even thermoplastics. A similar laser welding process used with the metallic backplate could also be used for a thermoplastic backplate [24]. Special attention should be paid to galvanic compatibility between the primary structure and the associated brackets.

C. Materials Selected for Initial Testing

Based on the above list, a couple materials have been selected from Table 1 for early testing. Based on the application review above, metallics are relatively mature, so this list focuses primarily on thermoplastics.

1. Carbon Filled Thermoplastics

PEEK CF30 (MIL-P-46183) is a high-performance option with some of the highest strength to density of all thermoplastics. It has static dissipative and limited thermal conductivity properties which could make EMI shielding and work well for avionics boxes [29]. However, they are typically more brittle than unfilled plastics [30]. Carbon may cause corrosion when coupled with some metals, especially if implemented in the thermal loop so testing would be required to verify for those locations [4].

2. Glass Filled Thermoplastics

PEEK GF30 (MIL-P-46183) and Ultem (PEI) 2300 (MIL-P-46184) are high strength options that are electrically and thermally insulative. These would not have as many galvanic compatibility concerns. These could be options for the vent, water loop, or structural brackets. However, they are typically more brittle than unfilled plastics [18].

3. General Thermoplastics

PEEK Natural (per MIL-P-46183) and Ultem (PEI) 1000 (per MIL-P-46184) are thermoplastic options that are more readily available and cheaper than glass filled, or carbon filled options. They also have better ductile properties than the glass filled, and carbon filled plastics [18],[19],[30].

4. Additive Manufactured Thermoplastics

Windform SP (Nylon 11 +CF) (AM) and Windform XT 2.0 (Nylon 12 +CF) (AM) have the highest strength to density ratios of all AM materials listed. These materials are favored over Ultem 9085 due to the increased strength to density ratios, and improved surface finish including the near invisible layer lines in SLS compared to the FDM process. Therefore, where AM is required to produce or simplify complex parts into one monolithic option, they should be considered. If the part's geometry can be machined, it is recommended to keep machinable plastics above as they have better strength to density ratios and a variety of similar or varying properties to suit each application. Testing and process controls may be required to define the anisotropy in the part, verify no voids or other defects, and characterize post process influence for designers.

5. Plating Thermoplastics

For any of the materials above, plating of the materials may be considered. Plating may provide a conductive and bonding layer to provide EMI protection and grounding, improve the galvanic couple to prevent corrosion, and potentially provide limited thermal and increased strength properties.

D. Selected Material Testing Standards

Limited testing has already been conducted for some of the materials above. A list of a planned initial set of testing with the materials above is included below:

1. General thermoplastics tests

The following list of general thermoplastic tests are intended to supplement existing vendor and MAPTIS data. A review of the existing data should be reviewed to verify that no tests are not already completed. This list is intended to show less common reported values that are important for spaceflight.

- ASTM-D4065 – Dynamic Mechanical Analysis (DMA) for temperature performance – An initial characterization using ASTM-D5026, DMA in tension, can provide evidence supporting applications across a range of possible environmental temperatures, including operations at cryogenics temperatures and identification of the glass transition temperature.
- ASTM-D256 – Izod Impact Test – An impact test such as the Izod may also be performed to verify operation at cold temperatures.
- ASTM-D7332 – Pull out test for fasteners – Inserts should be installed in the materials and pullout tests should be conducted to verify strength.
- ASTM-D3846 – Shear strength of plastic – Shear strength is often not reported for thermoplastics and would be beneficial to designers.
- ASTM-D570 – Water Absorption Tests – If the material is intended to be used in the water loop, then water absorption tests should be conducted to verify that the material does not appreciably expand.
- ASTM-E328 – Creep Test – A creep test should be conducted for thermoplastics to determine how much, if any, creep over time happens from an applied stress.
- ASTM-D2863 - Oxygen Index – For components used in the vent loop and oxygen test should be conducted to characterize the flammability of the material.
- ASTM-E595 – Outgassing – For components exposed to vacuum, this test should verify no outgassing
- NASA-STD-6001B – Off gassing/toxicity – evaluates to ensure materials in the ventilation loop do not produce toxic volatile vapors that can harm the crewmember

2. AM verification tests

- ASTM-D638 in relevant print orientations – If the vendor or MAPTIS data only reports data in one direction for an AM material, it is important that the material be tested in multiple planes. The lowest value is expected to be perpendicular to the layer lines due to layer to layer adhesion.

3. Plating on thermoplastics

The following tests are intended to verify the results of plating on thermoplastics. In addition to all the standard tests above, these following tests on the plated thermoplastics should be evaluated testing. It is noted that while there is not a general standard, an initial visual inspection is useful to determine any gross issues with the plating.

- ASTM-D7127 – Surface Roughness – These tests could help quantitatively determine if the plating job has provided a sufficiently smooth surface to seal interfacing components. Post processing may be required to reach sealing requirements.
- ASTM-C177 – Thermal Conductivity – Plating may change the thermal conductivity of the system, so thermal conductivity testing may be tested.
- ASTM-D638 – Tensile Properties – Plating can increase the strength of the material, so tensile testing would help to verify the change in strength.
- ASTM-D4935 – EMI Testing – Plating may be used to improve EMI shielding and must be tested to verify the EMI properties.

IV. Initial Testing Results

The following section outlines available testing results at the time of publication. Future testing from the list of gaps is part of future work.

A. Plating

Plating non-conductive plastics provides some challenges against traditional plating processes, leading to fewer vendor options. For this test series the top layer was a nickel plate, with an underlayer of copper. The vendors were instructed to plate to a total of 0.003" (76.2µm) as an amount for initial evaluation and comparison. There were no requirements on finish. A couple vendor processes were reviewed for quality of plating and tested for strength and other properties. Additionally, methods below for calculating performance compared to tested values are included for heat transfer and strength improvement.

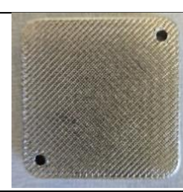
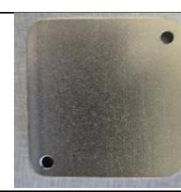
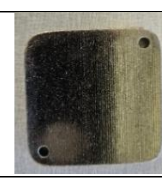
There is limited data on the exact process of plating for each company, although Repliform has studied and published plating methods for thermoplastics [16]. As a summary of the process, an electroless layer of nickel is applied 1 micron thick. Then it switches to an electrolytic process to apply equal parts copper (25 micron), ductile nickel (25 micron), and hard nickel (25 micron), to achieve the desired 0.003" thickness [16]. This method is like a production process developed for plating on plastics (ASTM B604-91) and follows ASTM B832-93, modified for structural applications [16]. Further studies may look at other thicknesses and processes each company offers.

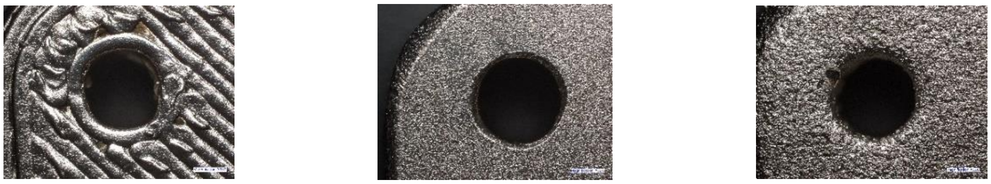
1. Sample Review

For the samples shown in Figure 2, there were four types of materials testing for plating, Ultem 1000 (machined), Ultem 9085 (FDM AM), Peek 30% GF (Machined), and Windform SP (SLS – AM). Three companies were reviewed: Repliform, SAT Plating, and QCP.

Upon a base visual inspection, there were no readily apparent flaws for all Repliform samples, QCP sample, and the machined SAT plating samples. The SAT Plating AM thermoplastics were not plated properly showing visible signs of the copper underlayer. SAT Plating and QCP were more reflective while the Repliform samples were Lastly, Windform SP was also reviewed with Repliform only for plating unfinished Windform SP and Windform's sanding (S-1) finish [17].

Figure 2. Plating Images

Repliform				
				
Windform SP S-1 Finish	Windform SP Unfinished	PEEK GF30	Ultem 9085	Ultem 1000
QCP	**SAT Plating**			
				
Windform SP S-1 Finish	Windform SP Unfinished	PEEK GF30	Ultem 9085	Ultem 1000



a) Ultem 9085 b) PEEK 30% GF c) Windform SP unfinished

Figure 3. Microscopic views of surface finish for Repliform.

Overall, plating post quality follows the quality of the material finish pre-plating. For instance in Figure 3, the unfinished Windform has a rough surface finish, and will still remain as rough after, although, the high-quality sanding S-1 finish that Windform offers prior to NASA sending it to plating, comes out with a much better finish that mimics the before and after roughness closely.

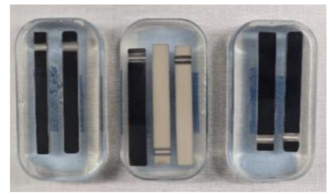


Figure 4. Cut plated samples.

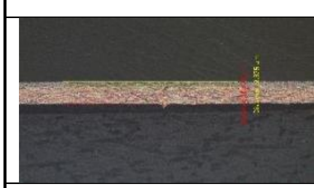
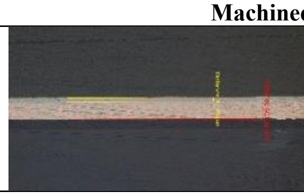
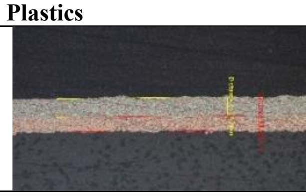
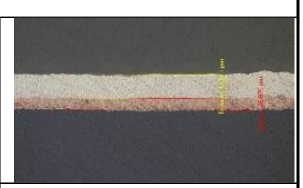
For quantitative comparison, the samples were cut, mounted, and polished in Figure 4 to review the cross section under a microscope. This was used to help show the quality and consistency of the plating thickness and show how the roughness affects the overall plating at a microscopic level. This was also compared to the 0.003" (76.2µm) requested by NASA in Figure 5. Three locations were measured for copper and nickel. Based on visual inspection, the plating was able to evenly plate across the entire surface and throughout the entire hole.

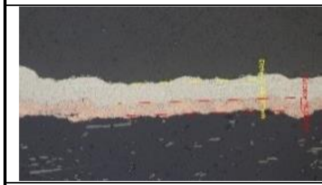
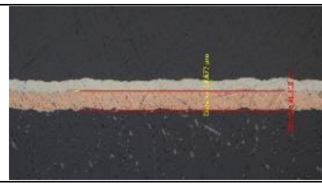
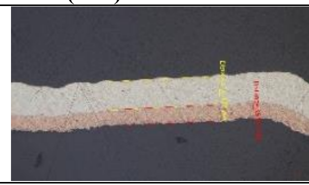
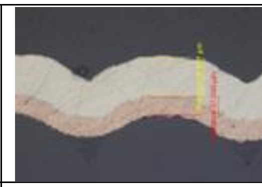
Table 3. Plating thickness review.

Sample (Company, Material) Thickness in µm	**Nickel Thickness avg. (std dev.)**	**Copper Thickness avg. (std dev.)**	**Total Thickness avg. (std dev.)**	**% difference (76.2 µm)**
SAT Plating, Peek 30% GF	11.9 (0.9)	37.6 (1.2)	49.4 (1.9)	43%
SAT Plating, Ultem 1000	10.2 (6.8)	38.8 (2.5)	49.0 (9.1)	44%
Repliform, Peek 30% GF	47.5 (1.1)	34.3 (2.9)	81.8 (3.2)	7%
Repliform, Ultem 1000	61.3 (4.0)	27.5 (3.0)	88.8 (5.4)	15%
Repliform, Ultem 9085 (AM)	70.9 (5.8)	35.4 (2.5)	106.3 (6.4)	33%
Repliform, Windform SP Unfinished (AM)	57.1 (12.3)	30.6 (2.0)	87.6 (13.2)	14%
Repliform, Windform SP S1 Sanding Finish (AM)	23.6 (1.8)	41.2 (0.1)	64.8 (1.9)	16%

For SAT Plating, the thickness had a large percentage difference less than the desired thickness. Repliform held close to the desired value, except for Ultem 9085. That material, however, had such a rough finish going in that it is difficult to measure an exact thickness as shown in Figure 5. There were no specifications for the thickness of the copper and nickel layer, just the overall thickness. Upon evaluation, SAT Plating favored a larger copper layer, while Repliform favored a larger nickel layer. According to Repliform's data they use different layers and types of nickel that are indistinguishable in the microscope but used to improve strength of the material [16]. In the future, standardizing this process, layer thickness, post processing, and target surface roughness values could be key to certifying plating in critical applications.

Figure 5. Microscopic cross sections of thermoplastic plating (0.003" plating) (200x magnification)

Machined Plastics			
			
SAT Plating, Peek 30% GF	SAT Plating, Ultem 1000	Repliform, Peek 30% GF	Repliform, Ultem 1000

Additive Manufactured (AM)			
			
Repliform, Windform SP Unfinished	Repliform, Windform SP S1 Sanding Finish	Repliform, Ultem 9085 (View 1)	Repliform, Ultem 9085 (View 2)

For the above images, they are separated by machined and additive manufactured plastics. The roughness of the additive manufacturing is evident here and demonstrates how the initial roughness significantly impacts the final roughness after plating. While the machined plastics have very good consistency, it is only the highly sanded (S-1 finish) Windform SP sample that shows a good surface finish consistency result.

Based on the results above, Repliform was used to plate materials for the following thermal and tensile tests. Their "ductile" metal coating process was chosen for below testing. The method was kept the same between all tests as a control, though future tests may vary some of the processes.

Table 4 lists the relevant properties of each separate material that are combined into a composite during plating. Based on Table 4, it is notable that metals being added may have 10 times strength properties, and 1,000 times greater thermal conductivity properties compared to the base thermoplastic material. This would suggest a thin layer of metal plating can have noticeable differences on the overall composite properties.

Table 4. Material properties used in plating.

Materials	Tensile Modulus (GPa)	UTS (MPa)	Thermal Conductivity (W/mK)
Structural Copper [16]	90	370	401*
Ductile Nickel [16]	140	860	90.7*
Hard Nickel [16]	146	1558	90.7*
Ultem 2300 [18]	10.4	175	0.31
Ultem 1000 [19]	3.35	115	0.122

*Based on pure nickel and pure copper properties [20]

2. *Thermal Testing*

With plating, one benefit could be thermal heat transfer. This could be especially important for items that see large temperature ranges exposed directly to the vacuum and solar radiation of space, as well as internal boxes such as those for avionics that produce heat that must be expelled since normal convective heat transfer with fans cannot be conducted in vacuum. A straight thermoplastic surface that is plated could allow heat to travel across it well, to avoid localized hot spots. If heat transfer is required through the surface, a secondary option, thermal vias, could be added through the surface. Thermal vias are holes through a low thermal conductivity material that are plated with a high conductivity material to allow thermal transfer through the plate. The closest equivalent to this application would be thermal vias on printed circuit boards that allow an integrated circuit that may create a lot of heat to transfer some through the circuit board to help avoid overheating [21]. In this case, this type of thermal via would be integrated in the case or structure as needed. A hole would be machined prior to plating and then the plating process would place the internal hole to allow heat transfer through the plate like a heat pipe. Since plating uses copper at its base which has high thermal conductivity, even the thin 0.003" thickness plating jobs can have a large effect on over thermal conductivity of a material. Some future research could look at making the holes small enough and plating thick enough to close the holes [21].

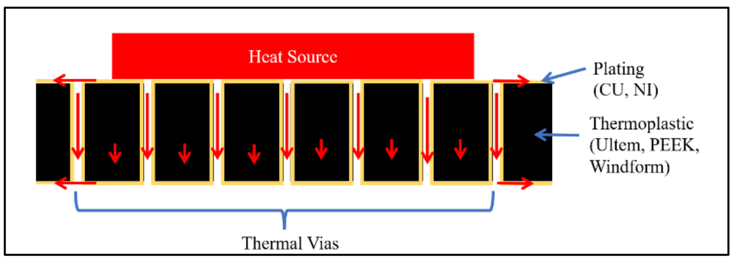


Figure 6. Plating thermal vias conceptual diagram.

Using thermal resistance equations for a steady 1-D system, an approximation of the heat transfer can be calculated using Equations 1 and 2. Δx is the thickness of the material, k is thermal conductivity, A is area, and R_{th} is thermal resistance. The equation looks at the system as an array of heat pipes and models with the lower thermal conductivity of most of the material. The resistance of the heat pipes and the plate everywhere else can be calculated individually using Equation 1. The equivalent resistance of all the heat pipes over the relative area can be estimated and added to the resistance of the plate everywhere else using Equation 2. Then the thermal conductivity can be re-integrated using the total resistance in Equation 1.

$$R_{th} = \frac{\Delta x}{k\,A} \quad (1) \quad | \quad R_{th,total} = R_{th,1} + R_{th,2} + R_{th,3} + \cdots + R_{th,N} \text{ [20]} \quad (2)$$

To verify this method a test plate has been manufactured. The test plate is 3/8" thick with holes that are 1/8" in diameter. The plate is then plated from Repliform at 0.003" thick. The total plate is 11.75" by 11.75" with varying numbers of holes. The Plate is then tested using a GHP Titan 456 for ASTM C-177. Estimates for the heat transfer are then calculated for a plate in Table 5 and the equations above.

Table 5. Thermal conductivity increase.

Sample #	#holes	note	Predicted Thermal Conductivity (W/mK)	Results
-	-	Ultem Vendor Specification [19]	0.122 (specification)	N/A
2	0	Plated 0.003"	0.124	0.119
3	25	Plated 0.003"	0.164	0.122
4	144	Plated 0.003"	0.361	0.151

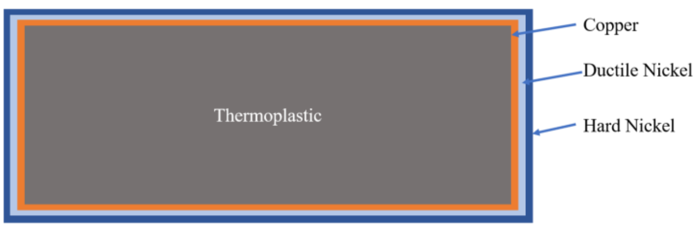
Based on the results there is an increase in thermal conductivity with the number of holes; however, it varies significantly from the prediction. There is also only one sample in this set. Further analysis is needed to evaluate either second order effects, or a second verification test on a different machine and add more samples. If the increase is only as much as tested, then higher thicknesses of plating may still be able to provide an appreciable thermal conductivity increase to meet requirements.

3. Plating Pull Tests (ASTM D638)

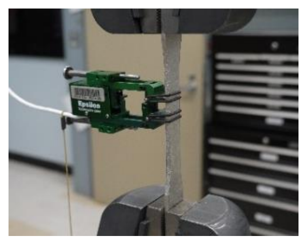
Another benefit of plating is strength increase due to the improved mechanical properties of the metals used in plating. This can help in many load cases, especially in bending where the material properties at the edge have the highest influence on overall bending properties. As a preliminary check of this capability to improve strength, some standard dog bone samples were pulled tested to validate basic equations used to model the properties and ensure the plating process still maintains the proposed strength as shown in Figure 7.

To model the properties for a tensile pull test with plating a rule of mixtures analysis can combine the properties into a composite property value. Essentially, the fractions of cross-sectional area can be combined to give the overall composite property. For Equation 3, E_c is the composite property (tensile modulus or UTS), f is the area fraction of material 1 relative to the total area of material 1 and 2, E_1 is the material 1 property, and E_2 is the material 2 property [16]. This equation can be stacked to combine all material properties into one. For example, layer 1 of copper can be material 1 and the plastic material can be material 2, then the result of that can be material 2 for the next equation and the nickel layer 2 can be material 1, and so on.

$$\boldsymbol{E_C = f\,E_1 + (1 - f)E_2} \quad [16] \tag{3}$$



a) Dog Bone Cross Section (not to scale)



b) Dog bone in test.

Figure 7. Pull testing plating samples.

For Testing, 20 samples were tested: 5 Black Ultem 2300, 5 Black Ultem 2300 plated, 5 Natural Ultem 2300, and 5 Natural Ultem 2300 plated. The black vs. natural was a secondary test being run concurrently. Prediction of the plated results were calculated based on the equations used above. The predictions and results are shown in Table 6.

Table 6. Pull test results.

	Plated Thick. (in.)	UTS (MPa) avg. (std dev.)	Tensile Modulus (GPa) avg. (std dev.)	Bending Stress (MPa)
Ultem 2300 Natural Properties	0	175	10.4	-
Ultem 2300 Natural Prediction	0.003	215	17.1	-
Ultem 2300 Black Prediction	0.003	186	17.1	-
Ultem 2300 Natural results	0	172 (1.3)	10.5 (0.9)	-
Ultem 2300 Black results	0	141 (1.2)	10.5 (1.5)	-
Ultem 2300 Natural results	0.003	201 (0.9)	18.1 (2.5)	-
Ultem 2300 Black results	0.003	176 (1.8)	18.2 (2.2)	-
ABS Flat [22]	0	19.1 (0.4)	-	-
ABS Flat Prediction	0.001	43.7	-	-
ABS Flat [22]	0.001	40.4 (2.1)	-	-
Ultem 9085 Flat [22]	0	60.7 (0.1)	-	71.4 (4.6)
Ultem 9085 Prediction	0.001	84.1	-	-
Ultem 9085 Flat [22]	0.001	67.2 (0.4)	-	97.4 (5.9)

As a baseline, the natural unplated samples were compared to reported material properties with a less than 2% difference. Comparing the black vs. natural showed that the tensile modulus was nearly identical, but there was an approximately 22% increase in strength of the natural over the black. Looking at the plating, there is a ~72% increase in tensile modulus for both black and natural samples. The natural sample showed a 17% increase in UTS, and the black showed a 25% increase in overall UTS. This difference in increase for UTS is expected, due to the lower initial UTS in the black Ultem. Across all pieces, there was an approximately 6% difference from the predicted values, with the difference in UTS being lower than the prediction and the tensile modulus being higher than predicted.

Another test series was conducted previously in the crew and thermal systems division in 2019 [22]. This test series looked at plating Acrylonitrile Butadiene Styrene (ABS) and Ultem 9085 and tested plated and unplated samples printed in different directions, and with pull tests mainly and one flexural test. This plating only plated 0.001" thick with 25 percent copper and 75 percent nickel (hard nickel assumed for prediction). For the ABS test, using the prediction method described above the prediction difference was only 9% with an increase of 108% UTS. For the Ultem 9085 the prediction difference was 22% with an increase of 11% UTS. For the lower strength plastics like ABS especially, this strength increase can be quite substantial; however, it is still recommended to look at some of the plastics that perform much better to begin with.

In general, the prediction method used above is a good starting value to predict the overall strength; however, in all cases tested the results were a little less than expected, though the exact reason is undetermined and may require further analysis and testing. On average the actual increase based on UTS is approximately 65% (std. Dev 25%) of the predicted value based on this sample set of 4 materials. The exact increase could be predicted more accurately by multiplying the ideal predicted value by 65%. A higher plating thickness could increase strength.

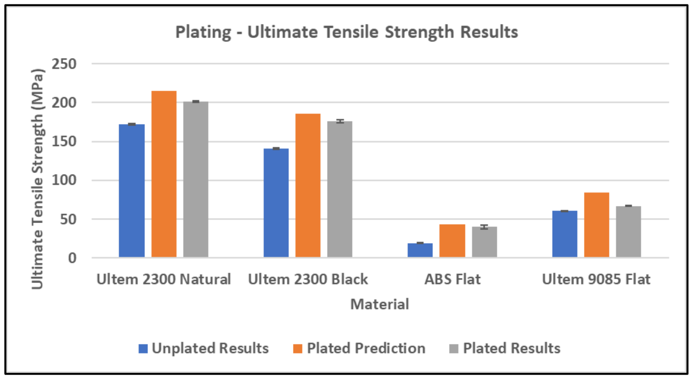


Figure 8. UTS results comparison.

B. Thermoplastic Insert Pullout Results

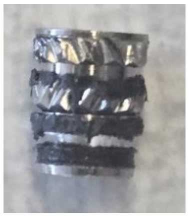
Another important element of using thermoplastics is fastening mechanisms. There are options to use heat set inserts or more traditional helical inserts. The xEMU PLSS commonly uses helical inserts in all aluminum components. Direct tapping is typically not recommended due to reduced strength in thermoplastics, though light duty applications may consider that as an option. In many cases, low performing thermoplastics common for hobbyists such as Polylactic Acid (PLA) will not tap well at all, and heat set become the only option. For the selection of the high-performance thermoplastics recommended above, testing was conducted to see how well heat set inserts and helical inserts perform.

To test performance, pull out strength is used as a metric. The sample is put in a tensile test machine with a bolt. The material held on the bottom and the bolt held on the top. A couple variations of this were tried in Figure 9. Of the tests, Figure 9.a used a large plate with many inserts spread apart Figure 9.b used thick plate samples per insert, and Figure 9.c used a cylindrical sample for each test. The last method may be favored for throughput testing and lowered cost, though more testing will be needed to verify if there are any substantial differences in results.

a) Many Inserts in Plate b) Single Insert in Plate c) Single Insert in Cylinder

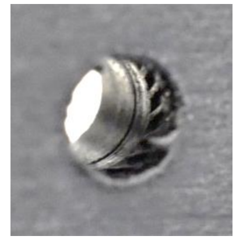
Figure 9. Thermoplastic pull out methods.

To potentially model and predict pull-out strength it is important to understand the failure mechanism. For both helical inserts and heat inserts, the insert mostly breaks out in shear. The pictures in Figure 10 show the remaining material after pull out. For the helical insert, the material shears throughout at the major diameter of the helical insert. For the heat set insert, the material shears where there is a clear cylindrical step down in plane across the circumference; however, the impression left in the hole for the angled ridges in the heat set insert indicates some level of plastic deformation occurring as well during pull out. An analytical approach for approximating the pull-out strength of helical inserts has been created below, though an approach for approximating a heat insert pull-out strength is still in development.



a) Heat Insert after Pull Out

b) Helical Insert after Pull Out



c) Impression Left in Material from Heat Insert Pull Out

Figure 10. Insert and hole after pulling out.

Reviewing Figure 10.b indicates the helical inserts fail in pure shear due to the remaining material left in plane with the insert circumference. This could be modeled with pure shear equations; however, shear strength data is often not tested for thermoplastics and may vary with anisotropic materials, so comparison data is unavailable but part of forward work. If shear strength data is available, Equation 4 is proposed to approximate the pull-out strength of a helical insert assuming it fails in shear. The area in shear is multiplied by the shear strength to get the approximate helical insert pullout strength. D_m is the major diameter of the tapped helical insert hole per NASM33537 Helical insert specifications "Tapped Hole: Major Dia, Class 2B", TPI is threads per inch. %Shear has been estimated at ~58% using Figure 10.b image of the insert in shear. Number of coils N is per NAS1130 Tangless Insert Specification's "Number of Free Coils". Over the relative length of the insert the percent of length that is the material that has been sheared becomes the %shear used in the equation below.

$$\boldsymbol{Helical\ Insert\ Pull\ out\ Strength\ (lbs)} = \left(\frac{\pi * D_m(in)}{TPI} * \%Shear * N\right)_{Area} * \boldsymbol{Shear\ Strength} \quad (4)$$

Heat inserts may be more complicated. Figure 10 a and c indicate some portions fail in shear, while there is some plastic deformation left in the impression. Therefore, test data may be required to inform future analysis.

A multiple series test was set up to gather data for different materials, different insert types (heat or helical), different inserts sizes, and different inserts lengths. For most of these data points, a count of 5 or more were tested to average the results and report a standard deviation. Different types of inserts were used typically favoring NAS1130 style tangless inserts, though some tanged were tested as well assuming the difference is negligible. Helical inserts were installed per NASM33537. The current summarized results are shown in Table 7:

Table 7. Thermoplastic Insert Pull Out Strength.

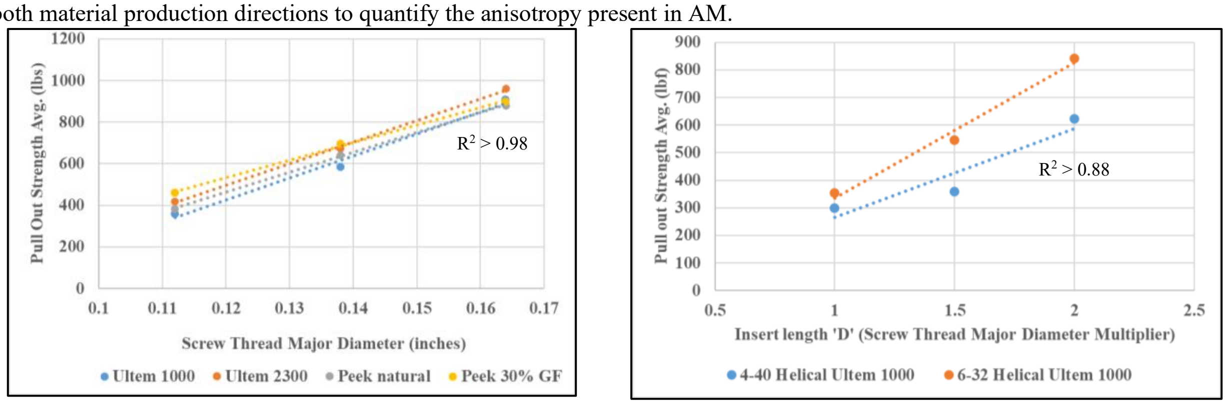
Hole Size	Type	Length/code	Ultem 1000 Black lbs‡	Ultem 2300 Black lbs‡	Peek natural lbs‡	Peek 30% GF lbs‡	Windform SP lbs‡
4-40	Heat Set	0.135" (IUC-440-1)	-	*	-	*	138 (10)
4-40	Heat Set	0.219" (IUC-440-2)	634 (30)	*	660 (24)	*	232 (25)
6-32	Heat Set	0.150" (IUC-632-1)	-	*	-	*	163 (22)
6-32	Heat Set	0.250" (IUC-632-2)	807 (18)	*	863 (55)	*	362 (38)
8-32	Heat Set	0.185" (IUC-832-1)	567 (52)	*	614 (56)	*	220 (43)
8-32	Heat Set	0.312" (IUC-832-2)	-	*	-	*	347 (20)
4-40	Helical	0.112" (1D)	300 (7)	-	-	-	-
4-40	Helical	0.168" (1.5D)	358 (43)	420 (38)	383 (85)	459 (82)	-
4-40	Helical	0.224" (2D)	622 (37)	-	-	-	-
6-32	Helical	0.138" (1D)	353 (33)	458 (60)	-	-	-
6-32	Helical	0.207" (1.5D)	582 (33)	672 (120)	641 (34)	694 (84)	366 (12)
6-32	Helical	0.276" (2D)	843 (49)	-	-	-	-
8-32	Helical	0.246" (1.5D)	908 (129)	960 (76)	880 (37)	897 (119)	-

*Could not gather data or not recommended for installation
‡Data for table above is shown as: Average - lbs (standard deviation- lbs)

From this table a couple of observations were noted. For all types, the length and diameter of the insert are the major driving factors pull-out strength. In general, the heat set insert of similar length performs similarly to the helical insert. For the glass filled materials (Ultem 2300 and Peek 30% GF) some data were gathered for heat insert; however, in most cases the insert was not able to be installed or required high pressure and install temperatures up to 800°F causing discoloration of the stainless-steel insert. Therefore, it is recommended to use helical inserts for glass filled materials. The empty boxes represent future work for more data to be gathered to fill out the table.

When installing heat inserts, there is often some beading up on the edges that must be sanded down or designed to avoid beading up carefully, which may provide variability in the results. Therefore, helical inserts may be preferred, as they provide similar results and are the more traditional insert type.

It is noted that quality of installation was critical to consistent high performing results. Some datasets with high standard deviations had some issues with installation due to varying levels of training. Some data with high standard deviation may be repeated with increased quality controls and procedures for future datasets. The AM materials should also be tested for pull out in both material production directions to quantify the anisotropy present in AM.



a) 1.5D Helical Insert Pull Out Strength vs Diameter b) Ultem 1000 Insert Pull Out Strength vs Length

Figure 11. Insert pull out strength modeled.

Plotting the data from Table 7 in Figure 11.a demonstrates that the pull-out strength follows a linear relationship. This graph also helps to verify that the data gathered maintained quality results to support this relationship across multiple test series (R^2 > 0.98). For the insert pull out strength vs insert length Figure 11.b demonstrates a relatively linear relationship between length vs pull, but with a lower R^2 value (R^2 > 0.88).

C. Water Absorption and Pull Tests

Another test series was conducted to determine the change in mechanical properties for Windform SP. This can be useful if the material is considered in the thermal loop of the PLSS. Twelve Type I dog-bone specimens were procured and pull tested to failure according to ASTM D638 [25]. Six of them were left dry, while the other six were soaked in DI water prior to testing. The following results shown in Figure 12 indicate a 7% decrease in average UTS between soaked and dry with only a 1–2% standard deviation. It also shows a 22% decrease in the manufacturers' tensile data. While there is a difference between dry and wet results, it has a very little relative difference. Furthermore, the manufacturer has tested Windform SP for water absorption according to ASTM-D570. The test results showed only a 0.10% change in weight of the sample after being immersed for 1 day [26].

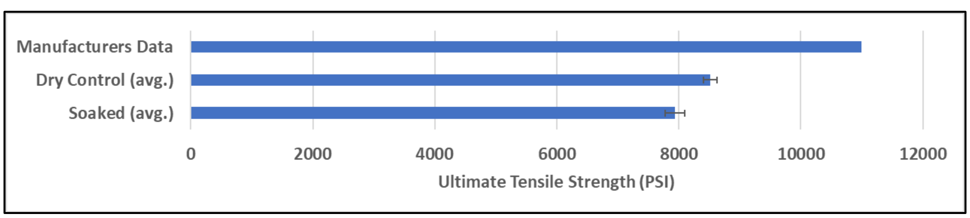


Figure 12. UTS for soaked Windform SP [25].

While this process shows Windform SP as a viable candidate in a water/thermal loop system, this is only preliminary and should be repeated for all other materials above.

V. Forward Work

A. Material Testing

The above data makes up a set of initial results and conclusions that may be used to help inform some initial hardware material choices; however, a full test series would be required. This should include and start with the materials and tests outlined above. This testing will help raise the TRL of each material considered for critical spaceflight to a level 3/4, which is about the level at which it is ready for infusion into relevant components and subsequent integrated testing. If plating is chosen a full set of tests will be required to verify both the composite material meets all requirements.

B. Hardware Infusion

After enough material tests for feasibility are conducted, materials that meet requirements may start to be integrated into PLSS components for evaluation in an integrated system. Machined thermoplastics should be certified and integrated first before considering AM thermoplastics. Most of the advanced thermoplastics in the table above could be integrated today but must be used with caution until a full suite of testing is completed. Integration with a system/component will help to raise the TRL of the component to 5/6 at which point the component is ready for integration into the larger system of the PLSS. A list of components to consider for infusion is included in the previous report [1]. It is recommended that machined thermoplastics are evaluated for PLSS components for testing, design, and certification first, then AM thermoplastics should be evaluated as a next step to simplify complex geometric shapes and reduce cross drills.

VI. Conclusion

Advanced materials should be included in future suit designs to lower the overall mass of the suit. Thermoplastics such as PEEK and PEI (Ultem 1000) should be considered as replacements for metallic components. Additives such as a Glass Fill or Carbon Fill of ~30% in the listed thermoplastics can improve overall strength. A Carbon fill would create a higher strength than glass fill and is static dissipative and conductive, although it does provide some concerns for galvanic compatibility depending on the material it is attached to.

Future work to be completed includes quantifying material properties key for spaceflight that are not included in basic and public vendor specifications. Tests for brittleness at cold temperatures, pull out test for inserts, water adsorption, creep test, and oxygen index should be characterized. Machined thermoplastics still have a large gap of testing and should be prioritized prior to AM thermoplastics. Further AM materials property characterization in applicable print orientation is recommended as anisotropic properties can influence design and manufacturing selection criteria. Lastly, plating should include testing for quality of plating and improved composite properties including surface roughness, mechanical properties, thermal properties, and EMI.

A set of initial tests was conducted for thermoplastics. For plated thermoplastics, vendors had some mixed results, though Repliform had good quality plating from inspection, and increased strength properties. There were mixed results for thermal conductivity increase that may need to be further investigated. For inserts, heat inserts and helical inserts performed similarly for pullout, although heat inserts did not work in 30% glass filled plastics. Heat inserts may also bead up during installation, so helical inserts may be preferred for the materials tested. Lastly, limited water absorption tests were conducted for Windform SP that showed little decrease in strength indicating that it could be a good candidate for the water loop, although further testing will be required to evaluate other materials.

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