Additive Manufacturing Efforts and Applications in Expendable Launch Vehicles

By:

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Introduction

Expendable Launch Vehicles are single use space rockets used for lifting payloads into space. The two primary expendable launch vehicle programs in use today are the Atlas V and Delta IV launch vehicles. Both vehicles are designed, manufactured, and launched by ULA headquartered in Centennial, Colorado. Both vehicles have a vast history dating back to the 1950s. This incredible history includes the launch of John Glenn, the first American to orbit the earth, all American Mars rovers, and the vast majority of national security satellites [1]. Such significant missions drive a very high standard of reliability. This high standard of reliability often suppresses innovations that other industries experience as new technologies must be proven repeatable and reliable to an extent that is not required of other industries. As a result of these high standards, the Atlas V and Delta IV programs use a significant amount of outdated technologies and processes. Advanced manufacturing methods such as Additive Manufacturing promise to help modernize the technology used by the Atlas V and Delta IV launch vehicles programs in an effort to significantly reduce cost, component lead times, processing and assembly hours, and enable advanced analytical techniques. This paper reviews the approach taken for utilization of Additive Manufacturing in the Atlas V and Delta IV expendable launch vehicle programs.

Additive Manufacturing Applications in Expendable Launch Vehicles

There are three main areas where Additive Manufacturing is being implemented in the Atlas V and Delta IV expendable launch vehicle programs: tooling, rapid prototyping, and both polymer and metallic flight hardware.

As expendable launch vehicles do require such high levels or repeatability and reliability, the first logical application of Additive Manufacturing is tooling. Additive Manufacturing has been used to produce tooling at ULA for several years now. Hundreds of tools have been printed that have not only resulted in significant cost savings but have also significantly reduced production cycle times. That is, the time in which it takes vehicle components to be manufactured and assembled at the production facilities. Figure 1 shows example tools that have been manufactured using the extrusion based process of Fused Deposition Modeling (FDM).

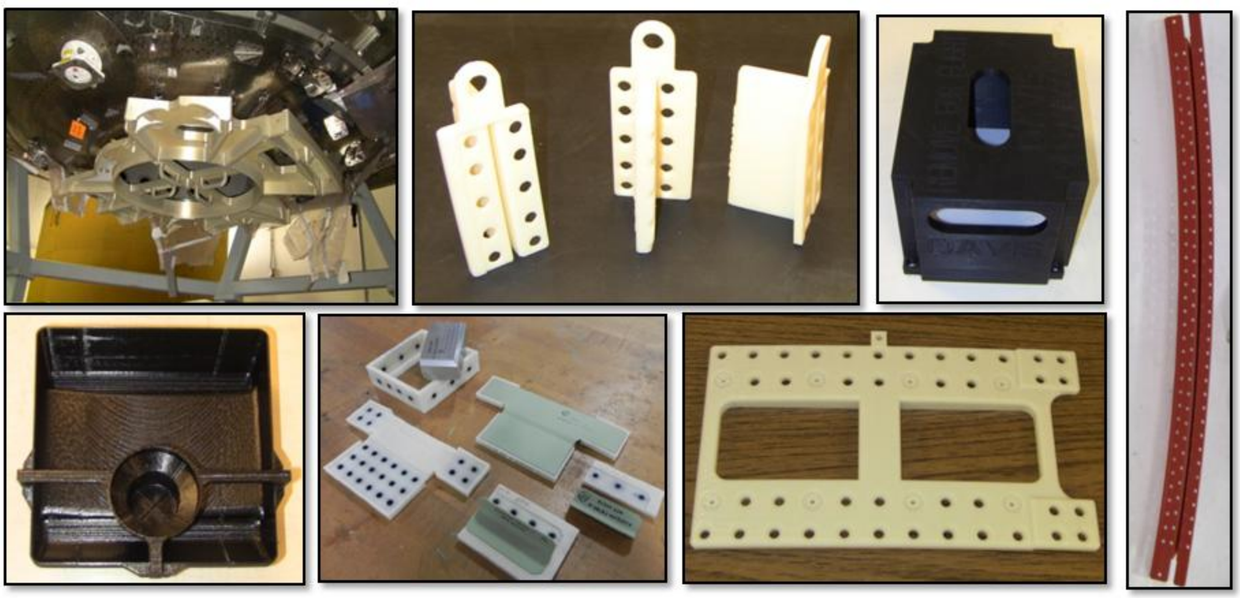

Figure 1: Example Additive Manufactured Tools

The figure shown above includes fastener drill templates, weld locating tools, destructive spray-on insulation molds, avionics box geometric stay-out zones, and bracket locating hardware. All tooling that is additive manufactured at ULA provides the production facilities one of two benefits. Either the newly printed tool shows a great cost savings as the tool would have otherwise been manufactured using more expensive, traditional methods or the tool is an enabler as the tool would not have been created if Additive Manufacturing was not available. Both cases represent a great benefit of Additive Manufacturing as it is applied to tooling.

The second application of Additive Manufacturing at ULA is rapid prototyping. Rapid prototyping allows for an abbreviated iterative design process flow for flight hardware. If an error is discovered during manufacturing of a traditionally released design package, a large amount of rework is required. Figure 2 represents the process flow of releasing a traditional engineering package. Figure 3 represents the process flow of releasing an engineering package using rapid-prototyping.

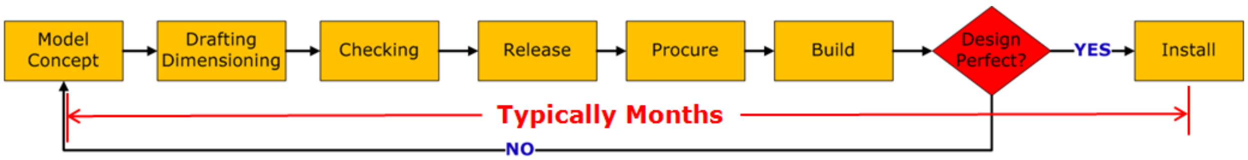

Figure 2: Traditional Engineering Process Flow

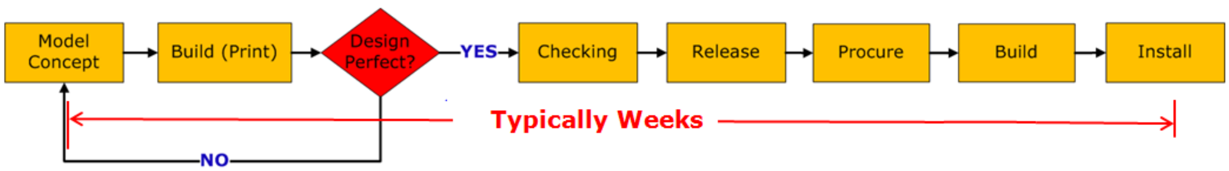

Figure 3: Engineering Process Flow using Rapid Prototyping

Through the use of rapid prototyping, additive manufacturing can identify design errors far earlier in the process and can cut months from the development cycle. This is true whether or not the end product is additively created. An important note is that related process innovations that additive manufacturing enables such as model-based definition for components that the end use product is additively created can even further reduce the engineering process flow.

Flight hardware is the most difficult and final application of Additive Manufacturing at ULA. Extensive testing has been performed to fully characterize the polymer material and process in order to qualify the material and process for flight use. Flight hardware is also the application that has the most potential benefit as the Atlas V and Delta IV product lines are expendable, meaning that new hardware is manufactured for each launch. During vehicle screenings that were performed in November of 2014, more than 150 additive candidates were selected for both Atlas V and Delta IV. These were both metallic and polymer applications that represented unique, complex geometries that drove expensive manufacturing methods. Additional important considerations included part consolidation opportunities, critical lead time reductions, potential to bring work in-house, and eliminating troublesome suppliers. Figure 4 shows a case study of a polymer additive manufactured flight assembly where Additive Manufacturing enabled significant component-by-component cost savings, extensive part consolidation, optimal conditioned air flow paths, and reduced weight when compared to the heritage system.

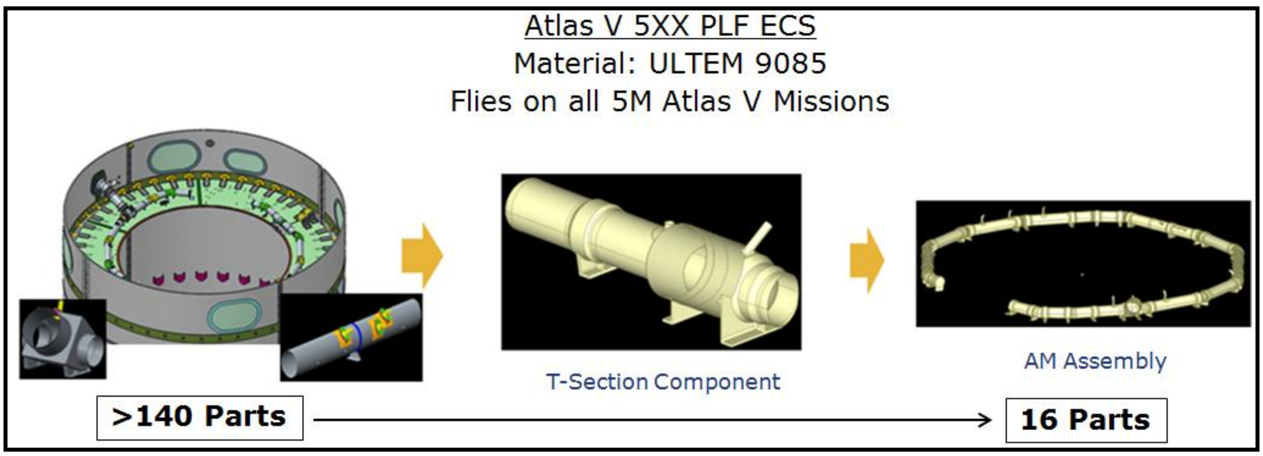

Figure 4: Example Polymer Flight Component

Current Technology at ULA

ULA currently has three additive manufacturing systems as well as a significant number of related technologies. All three systems use FDM technology. Figure 5 shows the current AM systems and materials at ULA.

Model	Fortus 900mc	Dimension 1200es
Technology	Fused Deposition Modeling	Fused Deposition Modeling
Material	Polymer •ABS •ABS –ESD7 •ULTEM 9085 •ULTEM 1010 •Nylon 12	Polymer •ABS
Build Volume	36″ X 24″ X 36″	10″ X 10″ 12″
Print Rate	~2 cubic inches/hr	~2 cubic inches/hr
Manufacturer	Stratasys, Inc.	Stratasys, Inc.

Figure 5: Current Additive Manufacturing Systems at ULA

The Dimension machine is primarily used for rapid prototyping and small tooling components. The two Fortus 900mc's are used for rapid prototyping, tooling, material testing, and flight hardware. ABS is a medium strength polymer used primarily for tooling. ABS – ESD7 is a modified form of ABS that is statically dissipative and used for avionics applications. One benefit of ABS material is that it has support material that is dissolvable in Sodium Hydroxide (NaOH). ULTEM 9085 is a high strength thermoplastic and is the material that ULA has fully qualified for flight use. ULTEM 1010 is a slightly different type of ULTEM material that has high better high-temperature characteristics. ULTEM 1010 would have great applications for composite layup mandrels as this material can withstand the high temperatures of autoclaves. Finally, ULA is pursuing a Nylon 12 material module as this material has exceptional elongation and has dissolvable support material.

ULA has a significant number of technologies that compliment the Additive Manufacturing capabilities. These technologies include, but are not limited to: an ATOS Digital Scanner to geometrically accept parts, a stereoscope, a 20 kip Instron tensile frame, a NaOH dissolver tank, and a High-Speed Digital Imaging Correlation (HDIC) system as well as software capabilities such as model-based definition and topology optimization. The digital scanner is primarily used for geometric acceptance of parts by means of overlaying a point-cloud on the nominal geometry to develop a contour plot of actual deviations from the nominal part geometry. The stereoscope and tensile frame are used to test the raw and as-built material, respectively. The NaOH tank is used to dissolve support material from components during post-processing and the HDIC system is used to obtain comprehensive dynamic response data during static or high-speed testing. Model-Based Definition eliminates dimensioning and drawing creations that are unnecessary when using Additive Manufacturing. Finally, topology optimization is used to design parts optimized for parameters such as strength, stiffness, and minimal weight.

FDM ULTEM 9085 Material and Process Qualification

ULTEM 9085 is the high strength polyetherimide thermoplastic that has been has been fully characterized and qualified for flight use manufactured using FDM. The material and process have been qualified through extensive testing. Appropriate processes have been developed to control and ensure that the final production parts are acceptable for use in flight applications.

The first testing performed was to define the specification controlled build parameters. The Fortus pre-processing software has a number of build parameters that can be adjusted. Figure 6 shows a visual representation of some of the build parameters that can are adjustable.

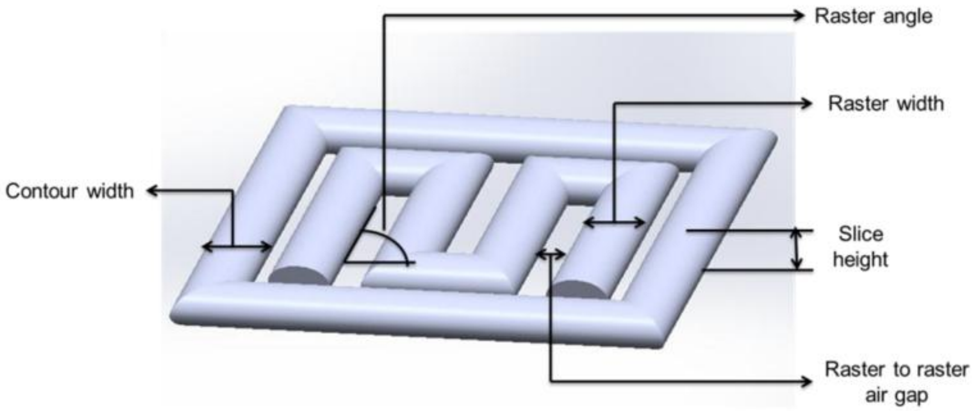

Figure 6: FDM Adjustable Build Parameters [6]

In addition to the parameters shown here are Contour to Contour Air Gap, Contour to Raster Air Gap, Number of Contours, and Parallel Offset which aligns the rasters and shifts each raster layer half of a raster width compared to the previous layer. These build parameters can significantly affect material characteristics. A set of 8 build parameters that were identified based on prior knowledge were tensile tested. The results were compared to one-another as well as to other aerospace company's testing results in order to select the specification controlled print parameters. The build parameters selected were those that resulted in the best out-of-plane strength. A further consideration that needed to be considered was surface roughness. Initially selected build parameters resulted in an unacceptable surface roughness as seen in Figure 7.

Figure 7: Unacceptable Surface Roughness

Surface roughness and strength are competing objectives in the FDM process. The optimal balance between both beneficial characteristics had to be selected. Through testing, modified air gaps were selected that found the optimal balance between acceptable surface roughness and strength.

Once the specification defined build parameters were selected, mechanical and thermal material characterization needed to be performed. Mechanical material characterization was performed first. Figure 8 shows the testing matrix that was performed to characterize ULTEM 9085 mechanical properties. All testing was performed using three lots of material. The temperatures were selected because cryogenic behavior of the material was unknown, a span of 75 F between data sets allowed for enough fidelity to permit linear interpolation between temperatures, and the advertised heat of deflection temperature of ULTEM 9085 is 307 F [3].

Property	Test	Test Method	Total Coupons	Environmental Test Conditions (˚F)															Notes
				-75			0			75			150			225			
				XY	XZ	ZY	XY	XZ	ZY	XY	XZ	ZY	XY	XZ	ZY	XY	XZ	ZY	
Tensile Strength, Modulus, Elongation, Poisson's Ratio	Tensile (Dogbone)	ASTM D638	85	5	5	5	5	5	5	5	5	5	5	5	10	5	5	10	Normalize and Pool Data, (10) Coupons at Hot-Wet
Compressive Modulus	Compressive	ASTM D695	38	2			2			10	10	10	2			2			Temp Knockdown
Bearing Strength	Bearing	ASTM D5961	38	2			2			10	10	10	2			2			Temp Knockdown
Interlaminar Shear Strength	Short-beam Shear	ASTM D2344	18	2			2			10			2			2			Temp Knockdown
Coefficient of Thermal Expansion	CTE	ASTM D696	6							3		3							Temperature range of 0F - 100F
Density	Density	ASTM D1622	3							3									1 on either side of print bed

Figure 8: Mechanical Property Characterization Testing Matrix

Figure 9 shows the test setups for each test above.

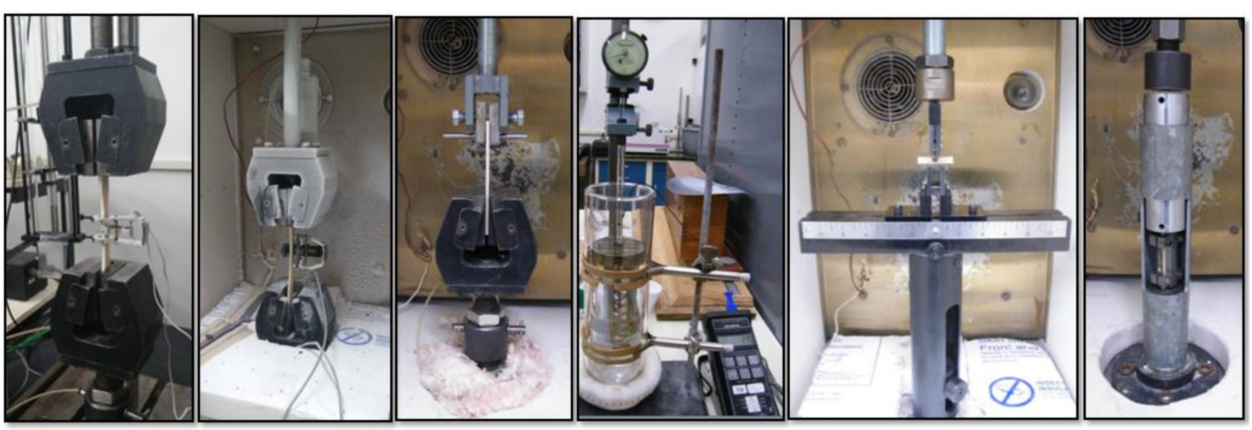

Figure 9: Mechanical Property Test Configurations

The following testing was performed in addition to the mechanical testing shown above: moisture conditioned tensile testing, moisture-freezing cycling, thermal vacuum testing, torque definition testing, torque relaxation (compressive creep) testing, geometric shrink due to differential cooling, and build volume thermal gradient effects testing.

All results were successfully obtained. This includes: all material properties, all MIL-HDB-17 [2] derived A and B Basis strength allowables, all applicable knockdowns or weighting factors dependent on moisture conditioning, temperature, orientation, and build location within the build volume, torque definitions dependent on fastener size and type, and geometric shrink factors.

The next step was to define all necessary thermal properties. Figure 10 shows the testing matrix that was performed to characterize ULTEM 9085 thermal properties. All testing was performed to the same lots of material and temperatures as the mechanical testing described earlier.

Property	Test	Test Method	Total Coupons	Environmental Test Conditions (˚F)															Notes
				-75			0			75			150			225			
				XY	XZ	ZY	XY	XZ	ZY	XY	XZ	ZY	XY	XZ	ZY	XY	XZ	ZY	
Thermal Conductivity	Thermal Conductivity	ISO DIS 22007-2	15	3			3			3			3			3			
Specific Heat	Specific Heat																		
Emmissivity (Hemishperical)	Emmissivity	ASTM E408-13	6							3		3							2 tan, 1 black (.060)
Absorptivity	Absorptivity	ASTM E903	6							3		3							2 tan, 1 black (.250)

Figure 10: Thermal Property Characterization Testing Matrix

Figure 11 shows the test setups for each test above.

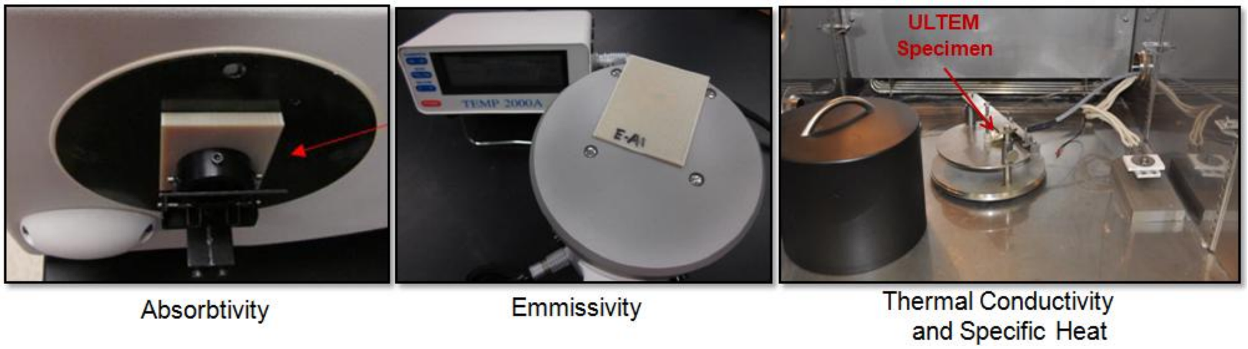

Figure 11: Thermal Property Test Configurations

All necessary thermal property values were successfully derived including the effects of temperature and build orientation of the component on the respective thermal properties.

Additional testing that has been performed includes multiple vibration tests to show that this material processed using FDM is not sensitive to a vibration environment. Vibration testing has been successfully performed to +6 dB over flight environments to prove that the material's structural integrity is not sensitive to vibrations. Figure 12 shows the test configuration of one such vibration tests.

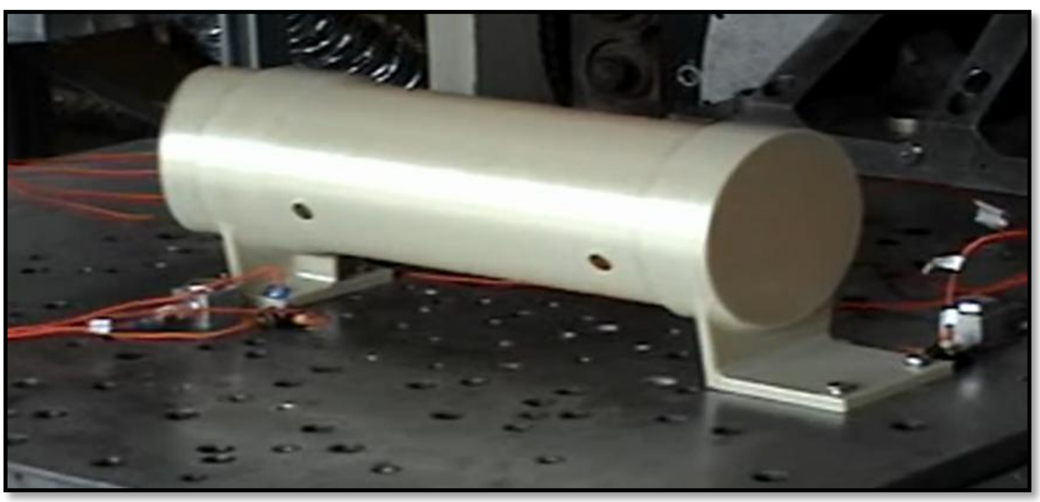

Figure 12: Vibration Testing Test Configuration

Successfully completing these vibration tests eliminates the need to vibration qualify or proof test specific designs and allows for the use of static equivalent load factors in the strength analysis of Additive Manufactured parts rather than complicated dynamic analyses.

The next steps in implementing FDM ULTEM 9085 for flight applications is sufficient material and process control. Both material and process specifications have been released that properly control both the raw material purchased for flight use as well as the process followed to pre-process, manufacture, and post-process flight hardware. The material specification includes lot traceability requirements, raw filament mechanical testing, and raw filament storage. The process specification defines the build parameters, machine qualification process, machine validation process, part finishing requirements, part geometric acceptance requirements, and part integrity acceptance requirements.

All data derived from the testing described herein and the process utilized to manufacture flight hardware was presented to the US Air Force, NASA, and Aerospace Corporation customers on April 17, 2015. This presentation successfully approved FDM ULTEM 9085 for flight use on Atlas, Delta, and next generation launch vehicles. This testing limits the material applications to -75 to 225 F. Applications that fall outside of these temperature ranges must be properly insulated until further testing approves the use of ULTEM 9085 beyond this temperature range.

Training Efforts

One very important aspect of implementing Additive Manufacturing is properly training the users of the technology. Training is currently being implemented that properly trains the engineers that are to design and analyze Additive Manufactured hardware. Four important aspects of this training exist: when to use Additive Manufacturing, the Additive Manufacturing process, how to best design and analyze for Additive Manufacturing, and all unique considerations and lessons learned.

The first critical training topic is when to use Additive Manufacturing. One key idea highlighted here is that Additive Manufacturing is a method of manufacturing intended to supplement other manufacturing technologies. It is not a fix-all solution. As Figure 13 Shows, Additive Manufacturing's niche is parts that have a high level of geometric complexity and a relatively low quantity of parts.

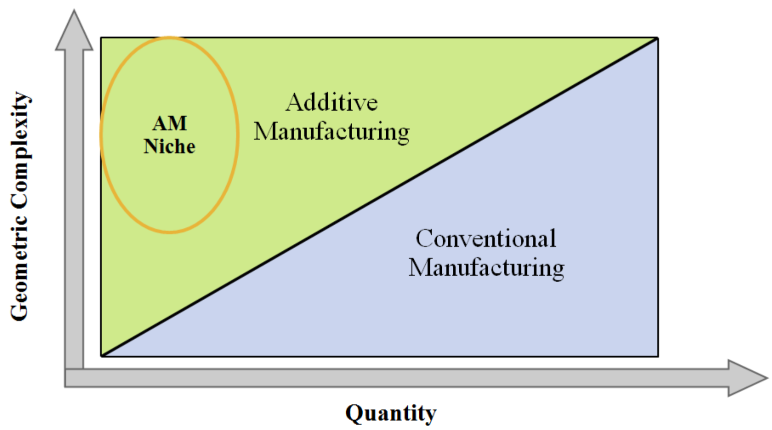

Figure 13: Training for Use of Additive Manufacturing [5]

The ULA Additive Manufacturing team feels that it is important for engineers that are going to be using the technology to have a basic understanding of the process itself. Figures such as Figure 14 are used to train the engineers as to how the FDM process works.

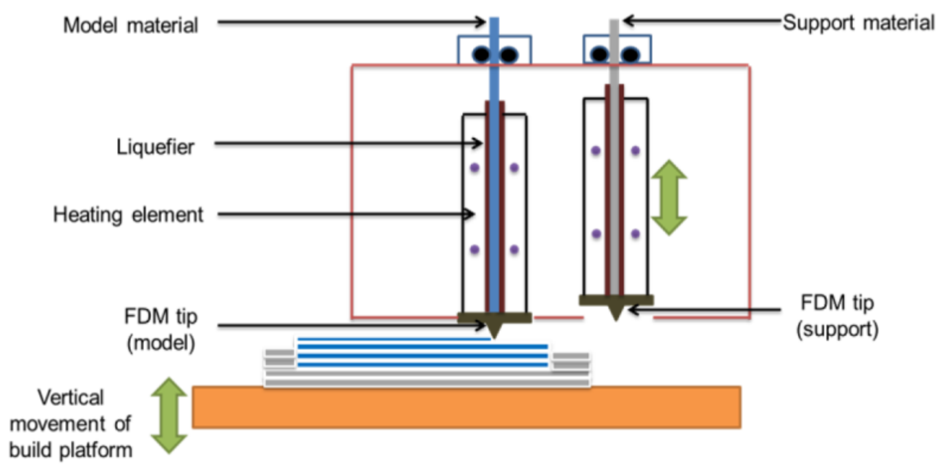

Figure 14: FDM Process Diagram [6]

How to design and analyze for Additive Manufacturing is perhaps the most important topic that an engineer using the technology must understand. Simply printing a component that is designed for traditional manufacturing is like forcing a square peg through a round hole [4]. It is forcing a technology on a design that was created for the limitations of traditional manufacturing. It is critical that ULA not only teaches the engineers what the limitations of the technology are but also to dream big in the sense that the part geometry can really be optimized in a way that cannot be done using traditional manufacturing methods. Topology optimization is an advanced analytical geometric optimization technique that the Additive Manufacturing training is to include.

Finally, much has been learned about the FDM process and Additive Manufacturing in general through the efforts that ULA has taken to implement Additive Manufacturing across the enterprise. Lessons and best practices will continue to be learned as Additive Manufacturing is further implemented across ULA. These lessons learned and best practices need to be properly communicated to all engineers that will use this advanced manufacturing technology through the training efforts described herein.

Future Efforts in Additive Manufacturing

ULA has only touched the tip of the iceberg with regards to utilizing Additive Manufacturing. Near term future efforts in Additive Manufacturing include additional testing to expand flight applications for polymers as well as metallic Additive Manufacturing material and process development.

The first efforts to be taken by ULA to further implementation of Additive Manufacturing are additional testing to expand flight applications for FDM polymers. Two sets of near term tests are planned to expand the applicable environments for ULTEM 9085. The first is cryogenic testing. During the mechanical characterization testing that was performed above, qualitative material properties were observed at cryogenic (-320 F) temperatures using Liquid Nitrogen. The concern for cryogenic applications was that the material would be embrittled to the point that it is no longer useful. Liquid Nitrogen testing showed that the material has significant elongation at cryogenic temperatures. Therefore, the next testing that will be performed is material characterization to -425 F using Liquid Helium in order to envelope Liquid Hydrogen applications (-420 F) as Liquid Hydrogen is the propellant used on both Atlas V and Delta IV second stages. The second set of testing is to instrument solid and sparse ULTEM 9085 specimens (reference Figure 15) and expose the material to the plume of a small scale rocket engine as seen in Figure 16.

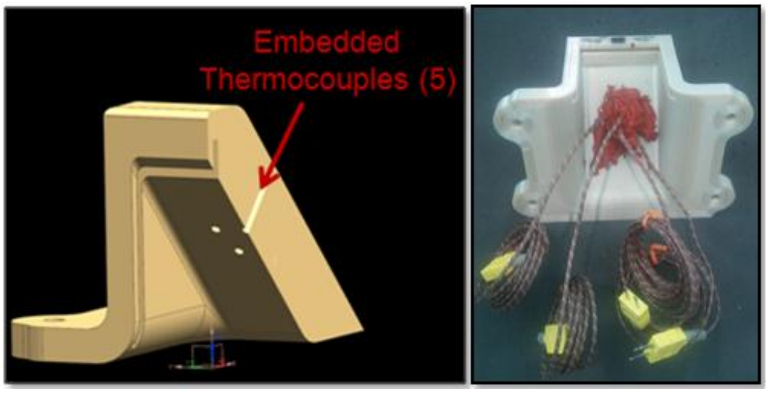

Figure 15: Instrumented Ablative Test Specimens

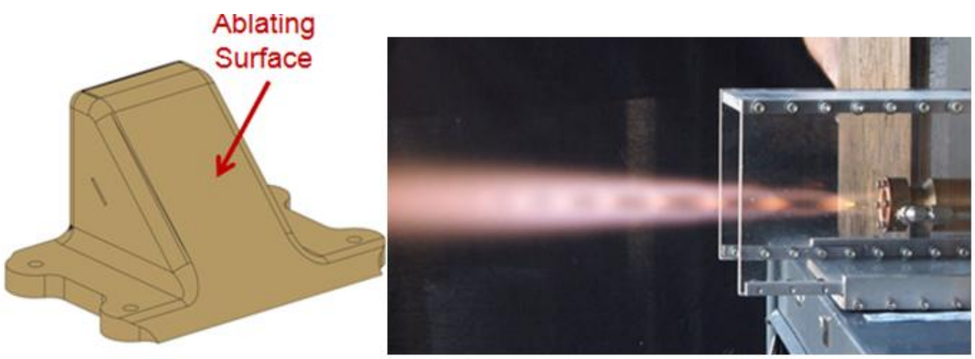

Figure 16: Conceptual Test Setup for Material Ablative Properties

The ablative testing proposed will quantify the material's heat, rate, and temperature of ablation. Testing instrumented coupons printed with a sparse core will also provide a proof of concept for a sacrificial, ablative layer separated from the structural aspect of the component by means of a poor thermally conductive path. If this concept proves viable, it will eliminate the need for thermal insulation on ULTEM 9085 hardware external to the vehicle that sees temperatures in excess of 225 F due to aeroheating.

Following the completion of ULTEM 9085 testing, the next step in implementation of polymer Additive Manufacturing is to qualify Nylon 12 material. The benefit of this material is the very high elongations that the material can be subjected to as well as support material that is dissolvable in NaOH. This allows for hardware to be designed that need not consider how support material will be manually removed.

In addition to the polymer materials testing and qualification, ULA is also pursuing the purchase of a metallic Additive Manufacturing technology and later the qualification of the metallic material and process for flight use. A trade study has been performed with assistance from Oak Ridge National Laboratories and NASA Marshall Spaceflight Center that led to the decision of purchasing a Concept Laser M1 powder bed system and dedicating this machine to Inconel 718. In addition to considerations such as cost, lead time, build rate, build volume, and in-situ quality tools, this decision was made largely on the fact that Marshall Spaceflight Center is fully characterizing this material with the Concept Laser LaserCUSING technology and making this information public in the NASA MAPTIS database. Partnering with Marshall Spaceflight Center will allow for ULA to qualify the process and material for flight use on a very condensed timeline.

Conclusion

Advanced manufacturing methods such as Additive Manufacturing promise to help modernize the technology that the Atlas V and Delta IV launch vehicles programs use in an effort to not only significantly reduce cost but also component lead times, processing and assembly hours, and enable advanced analytical techniques. Although a significant amount of effort has been performed to date, ULA has only touched the tip of the iceberg with respect to implementation of Additive Manufacturing into the Atlas V and Delta IV expendable launch vehicle programs.

References:

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