Additively Manufactured Composite Tooling

HIGH-PERFORMANCE THERMOPLASTICS OFFER EFFICIENCIES AND DESIGN FLEXIBILITY

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The advanced composites industry has a continual need for innovative tooling solutions. Conventional tooling is typically heavy, costly and time-consuming to produce. New applications, product improvements and the demand for faster, lower-cost tool creation challenge composite product manufacturers to innovate and remain competitive.

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FDM™ (fused deposition modeling) technology is an additive manufacturing process using high-performance thermoplastics. The FDM process builds objects layer by layer through the deposition of material, using information from a digital model. The process is typically faster and less expensive than traditional manufacturing technologies.

The combination of additive technology and FDM material capability offers a much more effective way to produce composite tooling. This includes both high-temperature (>180 °C), low-volume lay-up and repair tooling as well as moderate-temperature (<121 °C) sacrificial (washout) tooling. Compared with traditional materials and methods, FDM technology offers significant advantages in terms of lead time, cost, and simplification of tool design and fabrication, while enabling increased functionality and geometric complexity.

This paper forms an abridged version of the "FDM for Composite Tooling" design guide (referred to herein as "design guide") and provides an overview of the best practices associated with 3D printed composite tooling. It also provides relevant performance data and examples of effective tools designs. More detailed information can be found in the full version, available at: http://www.stratasys.com/solutions/additive-manufacturing/tooling/composite-tooling.

Background and Purpose

Traditional manufacturing methods for high-performance fiber-reinforced polymer matrix (FRP) composite structures require the use of hard tooling for the mold or mandrel that dictates the shape of the final part. The mold or mandrel is most commonly made of metallic materials (aluminum, steel, or Invar alloys), although non-metallic materials are also utilized (specialized composite tooling materials, high-temperature tooling board, etc.). Regardless of material, tool fabrication typically requires significant labor and machining, leading to high costs, material waste, and long lead times, consisting of many weeks for even relatively simple part shapes and many months for more complex tools. The use of additive manufacturing (or "3D printing"), and specifically FDM, for composite tooling has demonstrated considerable cost and lead time reductions while providing numerous other advantages such as immense design freedom and rapid iteration, nearly regardless of part complexity.

Stratasys FDM technology has been successfully utilized for low-volume composite lay-up and repair tooling applications for years, but was limited by the lack of materials capable of withstanding the 180 °C cure temperature frequently required for aerospace and similar high-performance structures, as well as a lack of design knowledge and guidance. FDM materials ABS (and ASA), PC, and ULTEM™ 9085 resin have been demonstrated to be effective to temperatures up to 85 °C, 135 °C, and 150 °C, respectively. With the introduction of ULTEM 1010 resin, FDM technology has demonstrated numerous advantages for fabrication of composite structures cured at temperatures in excess of 180 °C and pressures of 0.7 MPa.

Scope and Contents

The purpose of the design guide is to provide engineers, designers, and manufacturers of composite structures with the information and knowledge to effectively design, produce, and use FDM composite tooling, regardless of prior experience with or exposure to additive manufacturing. This paper provides a subset of the contents of the "FDM for Composite Tooling" design guide and is intended to inform readers regarding the general capabilities and key considerations for FDM composite tooling, although it will not contain the depth or detailed design aspects provided in the design guide itself.

TOOL DESIGN, PRODUCTION, AND USE

Just as design and construction aspects of traditional composite tooling vary depending on the material of construction (e.g., Invar vs. carbon/epoxy), there are factors and key considerations that are critical to the effective design and use of FDM composite tooling. In particular, in the context of the design and development of the mold or mandrel, it is important to understand and consider the processing parameters (e.g., cure temperature, vacuum bagging scheme, and pressure) for the composite structure, coefficient of thermal expansion (CTE), tool/part tolerances, and the intended use or application (e.g., tooling for small quantities of prototype parts vs. production tooling). All of these factors influence final design and construction of an FDM tool and are addressed in detail in the design guide and at a high level in the following information.

Cure Temperature

The cure temperature of the composite structure primarily influences material selection. FDM materials are capable of covering a broad range of cure temperatures, as displayed in Figure 1. As shown, ULTEM 1010 resin has the highest temperature capability of relevant FDM materials and also has the lowest CTE (refer to Section 2.2 of the design guide), making it the preferred

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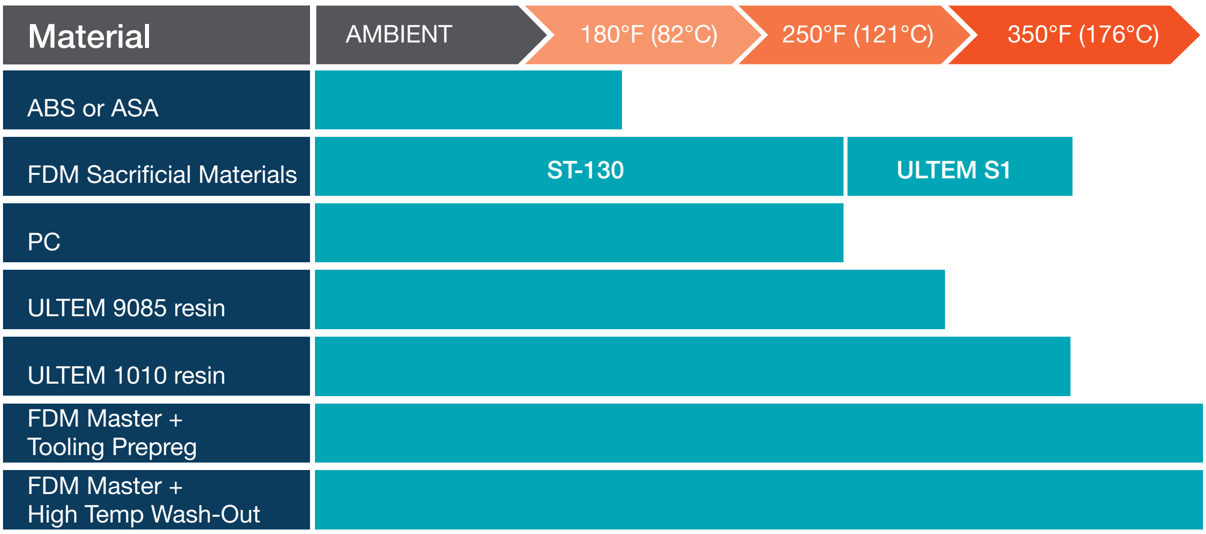

Figure 1 – Temperature capabilities of FDM materials.

and recommended choice for the majority of composite tooling applications. Thus, while tools made from PC and ULTEM 9085 resin can withstand the cure cycle for a 125 °C-cure material system for example, ULTEM 1010 resin is likely still the most appropriate choice to minimize expansion impacts.

Coefficient of Thermal Expansion (CTE)

CTE is an important consideration for nearly all composite lay-up tooling. The CTE was determined using thermomechanical analysis (TMA) per ASTM E831 for relevant FDM materials and can be seen in Table 1, along with that of common conventional tooling materials for comparison.

As a result of the relatively high CTE of FDM materials, it is an important consideration during tool design. Tool designs can and typically should be compensated for resulting dimensional changes. Detailed examples of such adjustments are provided in the design guide. In addition to geometric compensation, CTE differences between the tool and final part materials are also factors that impact tool type (male vs. female tools) and potential complexity. For male tools, sizing them to compensate for growth will frequently be adequate. And for some applications, such as mandrels for winding / wrapping, the CTE can be used advantageously to improve ply compaction and simplify mandrel removal. For female tools, particularly those with steep contours and deep drafts, additional care is required to ensure parts can be safely demolded without inducing tool or part damage.

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FDM MATERIALS	μm / (m•C°)	μin / (in•F°)
ABS / ASA	88	49
PC	79	45
ST-130 (sacrificial tooling)	106	59
ULTEM 1010 Support (sacrificial tooling)	58	32
ULTEM 9085 Resin	65	37
ULTEM 1010 Resin	47	26
CONVENTIONAL TOOLING MATERIALS	μm / (m•C°)	μin / (in•F°)
Tooling Boards	36 – 72	20 – 40
Aluminum alloy (AL 6061-T6)	25	14
Tool Steel	12	6.5
Carbon/epoxy	8	4.5
Invar	1.2	0.7

Table 1. CTE for FDM materials and common traditional tooling materials.

Accuracy / Tolerances

FDM is capable of producing parts (tools) with accuracies of ± 0.09 mm (0.0035 inch) or ± 0.04 mm / mm (0.0015 inch / inch), whichever is greater. It should be noted that all accuracies are geometry dependent (primarily due to the thermal nature of the process). Additional information on machine accuracy can be found on the Stratasys website (including a white paper on the topic). For development of the design guide, accuracy data was compiled for various representative tool geometries, both before and after thermal cycling – refer to Sections 3.1 and 4.1 of the design guide for additional details.

For composite parts that require greater accuracy than what can be achieved directly from the FDM machine, production of "near-net" shape tools, combined with skim-coat machining is a viable option. Additional development work is underway on this topic and will be provided in subsequent versions of the design guide.

Process Parameters and Tool Design

Fabrication process and cure cycle parameters, particularly cure pressure and vacuum bagging method, impact the design of FDM composite tools and specifically the "style" of the tool. FDM composite tools are primarily classified as "shell" style or "sparse" style (cellular) tools. The basic differences are as shown in Figure 2.

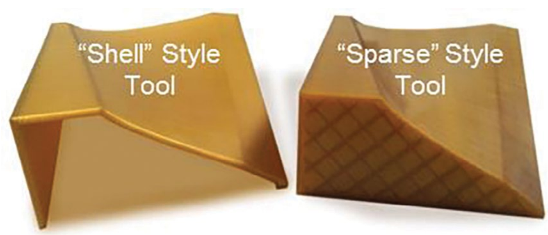

Figure 2 – FDM tool construction styles.

Shell style tools are effective for most applications, can withstand autoclave pressures exceeding 0.7 MPa, and are conducive to both surface and envelope vacuum bagging methods. And for many tool geometries, they are the most cost-efficient design as they minimize material

CONSOLIDATION PRESSURE		RECOMMENDED SPARSE DOUBLE DENSE SPACING		RECOMMENDED HEXAGRAM SPACING	
Metric	*US Customary*	*Metric*	*US Customary*	*Metric*	*US Customary*
Vacuum only – 0.3 MPa	Vacuum only – 40 psi	13 mm	0.5 inch	25.4 mm	1 inch
< 0.4 MPa	< 60 psi	6.5 mm	0.25 inch	25.4 mm	1 inch
0.55 – 0.7 MPa	80 – 100 psi	4 mm	0.15 inch	12.7 mm	0.5 inch

Table 2. Tool construction guidelines for envelope vacuum bagging.

usage and build time. Sparse style tools tend to have greater overall rigidity and stability and some geometries dictate the use of such a construction, as is demonstrated in more detail in the design guide. Sparse style tools can also be either surface (edge) or envelope bagged. When envelope bagging is used, additional guidelines regarding construction parameters (e.g., sparse-fill spacing) should be followed to avoid damaging the tool. General guidance for envelope-bagged, sparse-style tools is shown in Table 2, although results will vary somewhat based on geometry.

Tool Preparation (Post-Processing)

The FDM process inherently produces some level of internal porosity due to physical limitations of the extruded material beads, as can be seen in Figure 3, which shows the cross-section of tool paths (extruded material) for an example build layer. The process also produces perceptible build layers, which vary based on the shape of the part and the layer thickness. As a result, to ensure high-quality surface finish and vacuum integrity, post-processing of FDM tools is typically required.

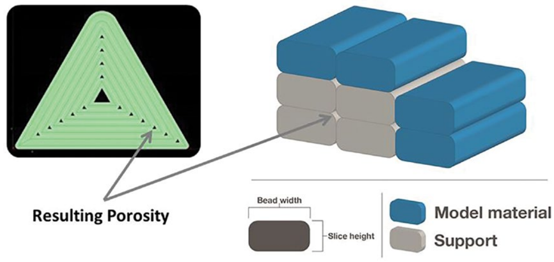

Figure 3 – Cross-section of FDM tool paths for an example build layer to illustrate the inherent occurrence of porosity (from Stratasys Insight™ software).

In preparation for use, tools are abraded to smooth out build lines, sealed, and then undergo a final polish, resulting in surface finishes consistent with typical industry requirements. Although requirements do vary somewhat across industries, typically a finish of 1.6 μm (64 μinches), Ra is considered acceptable. Using a standard process with progressively finer abrasive papers, a finish smoother than 0.4 μm (16 μinches), Ra can be consistently achieved on FDM composite tools. Sealing can be performed using a range of materials depending on the specific application. The most common materials used to date have been high-temperature, two-part epoxies. Epoxy film adhesives and adhesive-backed FEP films (and similar consumable products) have also been used successfully and have distinct advantages (e.g., ease of application), depending on the requirements of the specific application. Once sealed, common mold release agents can be applied in preparation for composite part lay-up (water-based released agents are recommended for applications with long-term exposure).

Evaluation of the impact of post-processing (sanding and sealing) on the accuracy of FDM tools was also performed and confirmed that minimal dimensional change occurs. Additional data is contained in the design guide and all accuracy characterization data was measured on tools that had been post-processed.

Tool Life

One of the final key considerations for effective design and use of FDM composite tooling is an understanding of the intended use or application of the tool. It is important to consider the intended tool life, or the number of anticipated parts to be fabricated. Tools intended for a few prototype composite parts can be constructed in a manner to minimize cost. Tools intended for a time-critical composite repair can be optimized for build time. And tools intended for longer-term production use and higher part volumes require greater scrutiny regarding nearly all aspects. Detailed examples are provided in the design guide.

The majority of usage to-date for FDM composite tools has been for relatively low part volumes (< 25 parts). However, in development of the design guide, tool life characterization testing was initiated; refer to Sections 3.3 and 4.3 of the complete design guide for more details. The available data indicates FDM composite tooling is capable of much longer tool life – 100s of cycles – depending on cure cycle process parameters of course. Additional tool life evaluation is ongoing to further characterize performance and will be provided in subsequent design guide releases.

TESTING AND CHARACTERIZATION

A subset of the testing and characterization that was performed during development of the design guide is presented in the following sections. Additional characterization work that was performed, but deemed somewhat more routine and is not presented herein, include outgassing (to verify a lack of potential contaminants), solvent exposure (to verify compatibility with the most common solvents used in composite fabrication facilities – IPA, acetone, and MEK), and surface roughness assessments before and after post-processing (to demonstrate and quantify resulting surface finishes). Details for these evaluations are provided in the design guide. All testing presented herein was performed on tools produced in ULTEM 1010 resin.

Accuracy and Thermal Stability

To assess accuracy and stability of FDM composite tools, multiple tools were evaluated both before and after thermal cycling. Three different tool designs were produced and build construction (shell vs. sparse build) and sizes were varied for a total of five variants. The tools were sent to an external inspection facility for precision 3D scanning. A Platinum FaroArm (from FARO® Technologies) with an SLP 300 laser head (from Laser Design, Inc.) was used. The scan data was compared to the CAD model for each variant using PolyWorks View 3D metrology software (from Innovmetric).

All composite tools used for this evaluation were post-processed (abraded) prior to the initial 3D imagery. This configuration was selected since nearly all FDM composite tooling will undergo such preparation prior to use, making the accuracy of a post-processed tool the most relevant data. Although there is likely some variability in post-processing between operators, the overall amount of material removed during abrasion was found to be quite small (using standard "best practice" procedures) and does not represent a significant portion of overall dimensional variation.

As stated, tools were scanned before exposure to elevated temperatures and then sent for thermal cycling. For cycling, the tools were vacuum bagged (envelope bagging scheme), heated to 180 °C, held at temperature for two hours (minimum) under full vacuum, and then ramped back down to below 65 °C between cycles for a total of 10 consecutive oven cycles.

Moisture Exposure

Many polymeric materials absorb moisture to some extent over time at various rates. Per the manufacturer (SABIC), ULTEM 1010 resin will absorb 0.7% when saturated (23 °C / 50% RH). Since moisture can be detrimental to composite laminate quality, relatively rudimentary testing was performed to ensure that such adverse effects can be prevented with basic precautions.

To ensure saturation and a "worst case" exposure scenario, two tools (one each shell style and sparse build constructions) were placed in a humidity chamber at 60 °C / 90% RH for two weeks. After conditioning, both tools were subsequently dried for 4 hours at 125 °C. Eight-ply quasi-isotropic carbon/epoxy laminates were then produced on each tool. The laminates were visually inspected after cure and then sectioned for microscopy to inspect for porosity, delamination, blistering, and other indications of moisture-induced effects. The primary objective was to demonstrate that even in the most severe climates, if moisture absorption becomes a concern, oven drying of tools prior to use is sufficient to prevent adverse effects on cured parts. In reality, most tools in a state of regular use are likely to be stored in environments far less harsh than those tested.

Tool Life

A thorough understanding of the potential useful life of a non-metallic tool is critical, particularly for production tooling consideration (or for any substantial part volumes beyond prototyping). It is also challenging information to obtain experimentally due to the time and resources involved. In working toward a preliminary baseline, both practical (empirical) and analytical data was gathered.

For empirical testing, the basic approach outlined for the accuracy and thermal stability testing described in Section 3.1 of the design guide was followed, but extended to higher numbers of thermal cycles. A single tool geometry (UAV fan blade), built in the two primary build constructions (i.e., shell and sparse build styles) was tested (the tools are as shown in Figure 2). Tools were cycled for 30, 60, and 90 cycles (180 °C, full vacuum, oven only), followed by evaluation (inspection and 3D scanning) and laminate fabrication (eight-ply, quasi-isotropic carbon/epoxy) with subsequent inspection and dimensional evaluation.

For the analytical portion, dynamic mechanical analysis (DMA) was used to evaluate creep in flexural specimens (3-point bend configuration). Isothermal testing was performed with a 0.7 MPa (100 psi) loading condition at multiple elevated temperatures (i.e., 180 °C, 195 °C, and 205 °C) and then time-temperature superposition (TTS) principles were used to form an understanding of long-term behavior. The basis for use of TTS comes from the demonstrated principle that viscoelastic behavior for a given temperature can be superimposed on data for a different temperature by shifting the curves along the time / frequency axis[1, 2]. It should be noted that the majority of loading applied to molds and mandrels is not flexural in nature, but rather compressive. Thus, evaluating flexural properties represents a “worst case” loading condition and ensures results are conservative, albeit slightly less directly applicable. An evaluation of compressive creep would be ideal, but such an apparatus was not available at the time of testing.

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RESULTS

Analysis of test and characterization data for accuracy, thermal stability and moisture impacts are provided in the design guide. Tool life evaluation was still in progress at the time of publication. As a result, preliminary results are provided herein. Data included herein was selected to be representative of and consistent with the broader results. As stated, all data is for ULTEM 1010 resin tools.

Accuracy and Thermal Stability

3D scanning of example tool geometries was performed both before and after thermal cycling, as described in Section 3.1 of the design guide. An example set of data can be seen in Figure 4 for the resulting comparison between the printed sparse style, UAV fan blade tool and the original CAD model data (no thermal cycling). As displayed, the scan data shows the tool has areas that vary from the model by as much as approximately 0.48 mm (0.019 inch). For reference, the subject tool is roughly 355 x 256 x 100 mm (14.5 x 10.5 x 4 inches) in size. Figure 5 shows the scan data for the same tool after 10 thermal cycles. As can be seen, there is very little dimensional change and the inherent variability and accuracy limits of the 3D metrology system itself certainly come into play as a likely source of the observed variation.

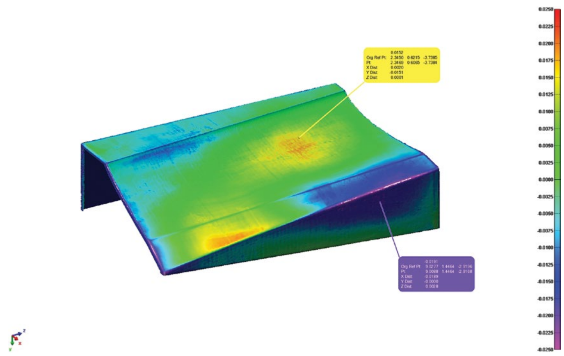

Figure 4 – 3D scan data for a UAV fan blade (shell style) tool with color map comparison to the original CAD model (no thermal cycling). Dimensions are in inches.

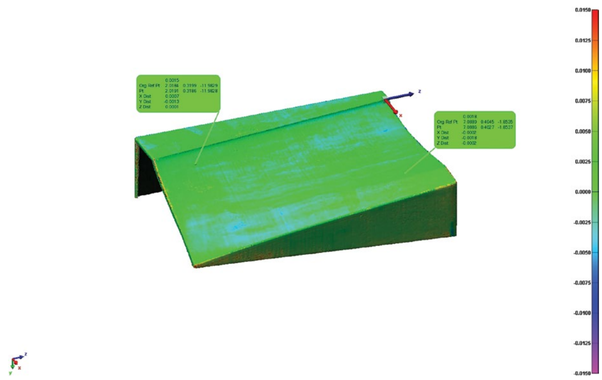

Figure 5 – 3D scan data for a UAV fan blade (shell style) tool after 10 thermal cycles with color map comparison to the 3D scan data for the same tool prior to cycling. Dimensions are in inches.

Moisture Exposure

As expected, moisture exposure testing demonstrated that tools dried (4 hours at 125 °C) prior to use produce laminates of acceptable quality (no significant porosity or other obvious issues).

Tool Life

The empirical portion of tool life characterization (as described in Section 3.3 of the design guide) showed 90 cycles, resulted in little deviation for the printed geometry, Figure 6. The localized maximum deviation measured was 0.145 mm (0.0057 inch) with an average deviation of less than 0.051 mm (0.0020 inch).

As previously described, DMA was performed to evaluate creep resulting from flexural loading (0.7 MPa) at 180 °C, 195 °C, and 205 °C. TTS was then used to project long-term behavior. The resulting relationship is shown in Figure 7. Again, it is important to note that this data was obtained under flexural loading conditions and is expected to be a significantly harsher loading condition than the actual cyclic compressive loading that composite tooling experiences in reality. That said, the results support that an ULTEM 1010 resin composite tool is capable of performing well beyond the requirements of prototyping volumes. The flexural strain at failure for ULTEM 1010 resin was determined to be 3.5% (tested per ASTM D790)[3]. Even a very low strain of 0.1% is not predicted to occur until 80+ hours of exposure at 180 °C and 0.7 MPa. Refer to Section 5 of the design guide for additional information.

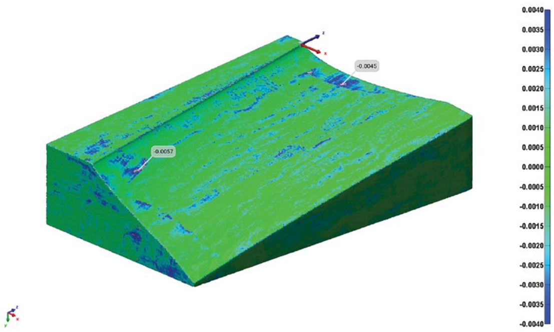

Figure 6 – 90 thermal cycles before vs. after dimensional comparison.

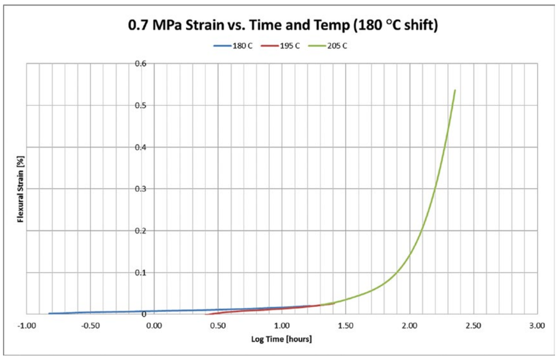

Figure 7. Flexural creep data for ULTEM 1010 resin test coupons shifted to 180 °C using TTS.

CONCLUSIONS

Stratasys FDM technology has been successfully utilized for low-volume composite lay-up and repair tooling applications for years. More recently, the introduction of ULTEM 1010 resin has enabled expansion of the technology into tooling for high temperature-cure (180 °C) composite structures. A comprehensive design guide has been developed to provide the information and knowledge to assist in unlocking the potential value of FDM composite tooling. A sub-set of the information assembled for the design guide was presented herein, including an introduction to the key considerations for FDM tooling, as well as some important characterization data.

Of particular importance, the tool life characterization work performed to date was found to be very encouraging. Given that the flexural strain at failure is 3.5% and even using a much lower threshold for acceptance, ULTEM

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1010 resin demonstrates the ability to perform under harsher loading conditions (flex) for the equivalent of dozens of high-temperature, high-pressure autoclave cycles, perhaps even 100+ cycles (refer to Figure 7). And of course, use of lower pressure (and/or lower temperature) cure cycles will only extend the usable life. This data also suggests that for use with the relatively low loading produced in vacuum-bag only cycles, tool life is not a significant concern for typical aerospace industry part volumes (at least from the perspective of creep-induced tool deformation). Further testing is necessary to confirm and develop a more comprehensive understanding and additional tool life characterization continues to be point of emphasis. Future development data will be included in subsequent versions of the design guide.

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