LARGE FORMAT ADDITIVELY MANUFACTURED TOOLING FOR OUT-OF-AUTCLAVE AEROSPACE COMPOSITES  (PREPRINT)

Scott R. Huelskamp and Tim Osborn

University of Dayton Research Institute

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**14. ABSTRACT (Maximum 200 words)**  
The aerospace composites industry is plagued with high costs and long lead times for tooling, driving up part costs and delaying design cycles in new production. Tooling also complicates sustainment efforts for the Air Force’s legacy aircraft. Large format additive manufacturing has the potential to address both issues. Printed thermoplastic tools in excess of 0.5 square meters in size will be presented that are capable of curing aerospace-quality epoxy and bismaleimide composites at lower cost and with much quicker lead times compared with conventional tooling. 3D-printable, high-temperature thermoplastics and reinforcing fibers will be investigated to achieve the right balance of strength, dimensional stability, and life from the tooling. A general approach for optimization of print parameters to achieve a high-quality tool will be explored. The ability of these additively manufactured tools to withstand autoclave cures as well as out-of-autoclave processes (some of which will require the tooling to support 7 kg/sq m (100 psi) single-side loading) will be demonstrated. The Air Force’s Low Cost Attritable Aircraft Technology (LCAAT) platform is especially suited for this technology and will be used as a demonstrator for this work.

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Scott R. Huelskamp, PE and Tim Osborn, Ph.D.
University of Dayton Research Institute
300 College Park, Dayton, OH 45469

ABSTRACT

The aerospace composites industry is plagued with high costs and long lead times for tooling, driving up part costs and delaying design cycles in new production. Tooling also complicates sustainment efforts for the Air Force’s legacy aircraft. Large format additive manufacturing has the potential to address both issues. Printed thermoplastic tools in excess of 0.5 square meters in size will be presented that are capable of curing aerospace-quality epoxy and bismaleimide composites at lower cost and with much quicker lead times compared with conventional tooling. 3D-printable, high-temperature thermoplastics and reinforcing fibers will be investigated to achieve the right balance of strength, dimensional stability, and life from the tooling. A general approach for optimization of print parameters to achieve a high-quality tool will be explored. The ability of these additively manufactured tools to withstand autoclave cures as well as out-of-autoclave processes (some of which will require the tooling to support 7 kg/sq m (100 psi) single-side loading) will be demonstrated. The Air Force’s Low Cost Attritable Aircraft Technology (LCAAT) platform is especially suited for this technology and will be used as a demonstrator for this work.

1. INTRODUCTION

Composite structures are used extensively in United States military aircraft. Structural composite materials in new aircraft, such as the F-22 and F-35, account for as much as 25-35% of the structural weight of the aircraft [1] [2]. The tooling needed to fabricate these structures represents a very significant investment to aircraft manufacturers in terms of cost and time. For large and complicated structures, it is not uncommon for the tooling to cost hundreds of thousands of dollars and require a six to twelve month lead time.

Within the United States Air Force, there is a push to develop agile tooling that allows new variants of aircraft to be built quickly. This would allow rapid insertion of aircraft into a conflict that are specifically suited to the mission. At the same time, tightening defense budgets are requiring lower cost options in the manufacture of these aircraft. The Air Force Research Laboratory’s (AFRL) Low Cost Attritable Aircraft Technology (LCAAT) concept embodies both of these mantras [3].

In addition to new production, legacy military aircraft built as many as 50 years ago also contain composite structures. Maintaining these aircraft is particularly challenging because much of the tooling used to manufacture the aircraft has been scrapped or is in significant disrepair. Replacement parts are no longer stocked by the original equipment manufacturers or the military. Delays and costs are considerable when an obsolete component breaks and is in need of
replacement. If the component is flight critical, this leaves the aircraft grounded and seriously degrades the readiness of the Air Force. For instance, the Air Force’s B-1B bomber has a readiness level of less than 50 percent, which effectively cuts the fleet size in half at any given time [4].

There is a strong need in aerospace for affordable, rapid tooling capable of low volume production in both new production and in sustainment. Additive manufacturing (AM) is an avenue to address this need, but material and equipment constraints have limited its adoption in the past. The primary constraint was the absence of a material capable of withstanding 180 degree Celsius autoclave cures that was also compatible with additive manufacturing equipment of the scale needed for aerospace structures. Recent developments led by the University of Dayton Research Institute have removed many of these constraints.

The study reported in this paper shows the implementation of newly developed feedstocks for large format additive manufacturing to produce composite tooling that is capable of withstanding 180 degree Celsius cures. Tool durability and dimensional tolerance were investigated to better understand the economics associated with this tooling approach. Also, in an effort to support out-of-autoclave processes that are expected to become more widely implemented in industry, the tooling was evaluated for compatibility with out-of-autoclave resin and processing techniques.

2. EXPERIMENTATION

2.1 Materials

2.1.1 Tooling Materials

Multiple high temperature thermoplastic compounds were developed for this work. Two were selected for further evaluation and are presented below. For comparison, one commercial off-the-shelf compound, already proven in large format additive manufacturing, was also investigated for lower temperature, out-of-autoclave applications.

2.1.1.1 Polyetherimide (Ultem 1000)

An Ultem 1000 polyetherimide (PEI)/carbon fiber pellet (5001, PolyOne), previously developed by UDRI and PolyOne for fused deposition modeling (FDM), was selected. The starting porosity of these pellets was measured to be an average of 10.4%, as determined through micrograph image analysis (Figure 1). Autoclave and out-of-autoclave fabrication trials were conducted on this tooling. The pellets were dried at 150 degrees Celsius for 12 hours before printing.
2.1.1.2 Polysulfone chemistry

A carbon fiber filled compound based on polysulfone chemistry (5003B, PolyOne), referred to as PS/CF2 in this paper, was also selected for printing trials. This material was previously developed by UDRI and PolyOne as a replacement to PEI in FDM printing for applications that do not require fire, smoke, and toxicity (FST) requirements. This effort was in response to long lead times and high costs related to PEI compounds. Pellet porosity was measured to be on average 2.09% using micrograph image analysis (Figure 2). The pellets were dried at 150 degrees Celsius for 12 hours before printing.
2.1.1.3 Acrylonitrile butadiene styrene (ABS)
An acrylonitrile butadiene styrene (ABS) compound with 20% by weight carbon fiber (LNP™ Thermocomp™ AC004, Sabic) was selected for low temperature, out-of-autoclave evaluations. This material is widely used in large format additive manufacturing.

2.1.2 Composite Materials
2.1.2.1 Prepreg
Cycom 5250-4 bismaleimide (Cytec) biaxial weave carbon fiber prepreg was used in this study to produce composite panels on the additively manufactured tooling using autoclave processing. This material is used extensively on military aircraft and represents the upper bound of cure temperatures that the majority of aircraft structures require.

2.1.2.2 Liquid Resin
R102/H18 epoxy resin (NONA Composites) was selected as an out-of-autoclave processing resin. This particular resin is able to reach a B-stage cure that is dimensionally stable without significantly heating the tooling, which gives the possibility of using low-cost, low temperature thermoplastics, such as ABS, in the construction of the tooling.

2.2 Equipment
2.2.1 Additive Manufacturing Equipment
Cincinnati, Incorporated’s (CI) Big Area Additive Manufacturing (BAAM) 1000 equipment was used in this study to print the thermoplastic composite tooling.

2.2.2 RapidClave
Globe Machine Manufacturing Company’s RapidClave® system was selected for out-of-autoclave processing on the composite tooling. The system is designed to replicate autoclave processing, but with very quick cycle times and minimal energy use. The system has been proven at Plasan Carbon Composites where it is used to fabricate Corvette composite hoods [5].

2.2.3 Metrology
The Handyscan 700 (Creaform) portable three-dimensional scanner and the accompanying VXelements/VXmodel software were used to scan the tooling surfaces and compare them to CAD models and other tool scans.

A SurfCom 130A profilometer was used to measure surface roughness of the tooling.

2.3 Processing
2.3.1 Printing
Two tool geometries were selected for printing on BAAM. The first was a leading edge tool section for the LCAAT platform obtained from AFRL in Dayton, Ohio (Figure 3). The tool has
a cross-section of 380 mm by 380 mm and is 700 mm long. The second was a generic tool representative of tooling needs for the Navy, referred to as the “Navy Tool” for the purposes of this paper. It measures approximately 400 mm by 660 mm (Figure 3). This tool geometry was provided by engineers at Fleet Readiness Center East in Cherry Point, North Carolina.

2.3.1.1 PEI Print

The Navy tool was selected to validate the printability of the PEI material on BAAM. At the time of this printing, very little work had been done on printing high temperature thermoplastics on the BAAM equipment. The majority of previous work was done with ABS compounds that process at much lower temperatures and with different machine parameters. During PEI print trials, it became clear that the extrusion nozzle was not adequately heated for processing high temperature thermoplastics. During any pause in the printing, the PEI would cool and freeze in the tip. This was partially mitigated by wrapping additional insulation around the tip and limiting pauses in the printing between build layers as much as possible.

The initial print trials were performed on PEI build sheets. Due to a combination of the smooth texture of these sheets and the relatively cool temperature of the sheet as compared to the extruded material, the prints would not adhere to the build sheet. The PEI build sheets were replaced with ABS build sheets and the subsequent prints adhered as desired.

A successful Navy tool was ultimately printed for tool evaluation. During the printing of the tool, machine parameters were being changed in real-time to limit print defects. Raw material quantity and sub-optimal machine hardware prevented the optimization of these parameters prior to tool printing. As a result, no meaningful parameter settings can be reported on this material.

2.3.1.2 PS/CF2 Print

PS/CF2 printing commenced after the PEI prints and previous ones conducted with earlier versions of the PS/CF2 material. A high compression screw and additional heaters were used to process the material [6]. Based on the lessons learned from the previous prints, the team was able to quickly identify the ideal processing parameters for this material. These are reported below in Table 1.

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Figure 3. LCAAT leading edge tool (left) and Navy tool (right)
Table 1: Final print parameters for PS/CF2 material print

<table>
<thead>
<tr>
<th>Bed Temp (deg C)</th>
<th>Extruder Temp (deg C)</th>
<th>Feed Rate (mm/sec)</th>
<th>Extruder Rate (rpm)</th>
<th>Bead Width (mm)</th>
<th>Layer Height (mm)</th>
<th>Tip Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>Zone 1: 350</td>
<td>Zone 2: 400</td>
<td>Zone 3: 350</td>
<td>Zone 4: 343</td>
<td>Tip 1: 355</td>
<td>Tip 2: 355</td>
</tr>
</tbody>
</table>

It is important to note that the heater in Zone 2 was malfunctioning during the print trials. In later prints, the temperature settings in Zones 1 and 3 were increased to compensate for this. It is unclear if this had an effect on the final print.

The efficiency in arriving at successful prints allowed both the LCAAT leading edge tool and the Navy tool to be printed using the PS/CF2 material, although only the Navy tool was used for further evaluation.

2.3.1.3 ABS Print

The ABS material is a standard material offered by CI and its processing is well understood by their staff. A LCAAT leading edge tool was printed with this material using CI’s standard process.

2.3.2 Coating and Finishing

2.3.2.1 Developmental Coating

A reliable high temperature coating solution for large format additively manufactured tooling has not yet been offered in the marketplace. As a result, an epoxy-phenolic coating (ToolCoat, UDRI) previously selected by UDRI for coating fused deposition modeling (FDM) components was used to finish the PEI Navy tool and the PS/CF2 tooling. The tools were first annealed in an oven (ramp to 216 degrees Celsius and hold 4 hours) to remove residual stress, machined to tolerance, then spray coated with the epoxy-phenolic. The final surface was sanded with 320 grit sandpaper and mold released with Frekote 770-NCT™ (Loctite).

2.3.2.2 Commercial Coating

Tru-Design (Knoxville, Tennessee) applied their commercially available TD Coat RT coating to the ABS LCAAT leading edge tool (Figure 4). This coating is specifically designed for large format additively manufactured ABS tooling. The coating was applied to the as-printed tool, hand finished, and had a final gel coat applied to yield a high-gloss tooling surface. No attempt was made to achieve a predetermined dimensional tolerance.
2.4 Composite Fabrication

2.4.1 Autoclave

Four plies of 5250-4 prepreg, approximately 300 mm by 300 mm, were laid up and bagged to the PEI Navy tool. All plies were laid at 0/90 degrees. Porous Teflon was laid under the prepreg to serve as a barrier ply against the tooling surface. The composite was bagged so that only the top surface of the tooling was under vacuum. The vacuum port was kept off of the tooling by running the vacuum bag off of one edge of the tool.

The tool and lay-up were loaded into an autoclave. A leak check showed no discernable leak over 5 minutes. The lay-up was cured according to manufacturer’s instructions, reaching a maximum temperature and pressure of 190 degrees Celsius and 7 kilogram/square cm (100 psi).

2.4.2 Out-of-Autoclave

Two methods of out-of-autoclave processing were evaluated during this investigation.

2.4.2.1 NONA Composites Epoxy Resin

The ABS LCAAT leading edge tool was given to NONA Composites to demonstrate their out-of-autoclave epoxy resin. Four plies of standard modulus carbon fiber quasi-isotropic braid (QISO-H-59.2, A&P Technology) were laid onto the tooling and infused with their R102/H18 resin system using vacuum infusion processing. The resin was mixed and degassed according to the manufacturer’s recommendations. The initial cure for the composite was four hours at 45 degrees Celsius, with a maximum part exotherm recorded on the bag side of 53 degrees Celsius. After demold, the composite was subjected to a freestanding post cure as follows: 25 to 60 degrees Celsius (0.3 deg C/min ramp), 60 to 100 degrees Celsius (1 deg C /min ramp), 100 to
180 degrees Celsius (3 deg C/min ramp), 180 degrees Celsius hold for 120 minutes, and cooldown (1 deg C/min ramp) [7].

2.4.2.2 RapidClave® System

The process used by the RapidClave® can be roughly approximated by vacuum bagging a tool down to a rigid surface and subjecting it to autoclave pressure. For this study, this substitution was used in lieu of RapidClave® cycling to determine the effect of loading an additively manufactured tool.

The tool was covered in breather material and vacuum bagged to a rigid steel plate so that autoclave pressure would compress the tooling against the plate. The tool was ran through three autoclave cycles: (1) ramp to and hold at 120 deg Celsius with 7 kg/sq cm (100 psi), (2) ramp to and hold at 150 deg Celsius with 7 kg/sq cm, and (3) ramp to and hold at 180 deg Celsius with 7 kg/sq cm (100 psi). No prepreg was used during these runs.

3. RESULTS

3.1 PEI Tooling

Defect-free printing was initially difficult to achieve with the PEI. This was primarily due to the fact that there was an unheated dead-zone in the nozzle tip causing rapid cooling of the polymer as previously mentioned. This led to prominent start-stop defects in the prints that were only partially addressed through insulation and print dwells.

Cross-sections of sample prints indicated that the tool contained inner-road porosity ranging from three to eight percent, indicating that the extrusion process removed or condensed a portion of the porosity originally seen in the pellets. Previous FDM prints conducted by UDRI using the same lot of PEI pellets yielded print porosities of nearly 13%. Because composite tooling was successfully made with this level of porosity from the FDM prints, the PEI BAAM prints were deemed acceptable.

Two Navy tools were successfully printed. The better of the two tools (Figure 5) was +3.0 mm/ -6.5 mm away from the nominal tool surface, as measured with the Handyscan 700, before machining. After annealing, machining, and coating, the actual tool surface was within +/- 0.2 mm from nominal. This was almost entirely driven by the accuracy of the CNC used to cut the tool.
3.1.1 Autoclave Processing

The resulting BMI composite appeared to be of high quality and comparable to a composite fabricated on conventional tooling. The tooling surface showed no visible damage after the composite was demolded. Some discoloration of the coating was observed outside of the vacuum bag, but this was expected (Figure 6).

After the autoclave cycle, the tooling surface was rescanned and compared to the scan conducted prior to the autoclave cycle. Total movement across the tool surface was within +/- 0.25 mm (+/-0.010”), although most of this movement was isolated to the extreme corners of the tool, outside of the composite trim zone. Almost 94% of the tooling surface stayed within 0.0127mm (0.005”) of the original surface.
3.1.2 Out-of-Autoclave Processing

After the autoclave processing of the tool was completed, it was subjected to the RapidClave®-like out-of-autoclave process. As described in Section 2.4.2.2, the tooling went through three cycles of increasing temperatures to determine if any tool movement would occur at any of the temperatures. After each cycle, the tooling surface was scanned and compared to the previous scan.

After the first cure cycle of 120 deg Celsius, movement of 0.2 mm (0.008”) was seen in one corner of the tool. Local deformation across the tool surface was below 0.05 mm (0.002”). After the second cycle, with a processing temperature of 150 deg Celsius, local deformation matched the previous run with no additional macroscopic movement. The third cycle run to 180 deg Celsius resulted in movement of 0.26 mm (0.010”) in one corner of the tool (opposite of the previously deformed corner). Localized deformation was again below 0.05mm (0.002”). See Figure 8.
The PEI Navy tool bottom was not perfectly flat due to some post-print warping that was seen during the initial annealing cycle. The large deformations are likely a result of the warped corners flattening back out against the steel plate. The minute localized deformations seen across the bulk of the tool surface indicate that very little, if any, permanent compaction or collapse of the tool occurred.

3.2 Polysulfone Chemistry Tooling

PS/CF2 printed well on BAAM, resulting in uniform and consistent bead structure (Figure 9). During flow rate trials, it was determined that the material could be printed at a rate of 44 kg/hr, although a lower deposition rate was used to allow sufficient cooling between layers and prevent a meltdown from occurring. This is a significant increase from the 36 kg/hr typically seen with other high temperature materials printed on BAAM [8].
The PS/CF2 tolerated extended periods of time at elevated temperatures in the extrusion barrel. Other high temperature materials previously processed on BAAM, such as polyphenylene sulfide (PPS), have a tendency to crosslink and increase in viscosity when held at their processing temperatures [9]. To prevent a complete lock-up of the compression screw with these materials, the BAAM operator must purge the extruder after every five minutes of inactivity, resulting in a waste of material and time. The PS/CF2 maintained its ability to be extruded after an hour of inactivity.

The PS/CF2 tool, after machining and coating, was vacuum bagged to check for vacuum integrity. A vacuum drop of less than 1.3 mm Hg was recorded in five minutes. In future work, the PS/CF2 tooling will be put through rigorous autoclave testing and analyzed for dimensional stability.

Inner road porosity measurements were not taken for the PE/CF2 material as printed. Given the lower pellet porosity of this material versus the PEI material, it is expected to be lower than the porosity recorded in the PEI prints.

3.3 ABS Tooling

The ABS tool printed well and the coating provided a high-quality tooling surface with a surface roughness of less than one micrometer, as measured in four locations across the tool. After demolding the cured composite and cleaning the tooling surface, the surface roughness was again measured at the same locations previously measured. All points measured below one micrometer again.

<table>
<thead>
<tr>
<th>Tool Surface Location</th>
<th>Pre-Infusion Surface Roughness (micrometer)</th>
<th>Post-Infusion Surface Roughness (micrometer)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>2</td>
<td>0.08</td>
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<td>0.04</td>
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</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>0.04</td>
</tr>
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</table>

In some areas of the tool, the carbon fiber braid used for the composite imprinted onto the gel coat and left rippled areas on the tooling surface. Due to a smoothing algorithm in the VXelements software, the magnitude of these imprints could not be determined.

The resulting composite was fully infused and well consolidated (Figure 10). It did not visually differ from comparable composites made on metallic tooling.
4. CONCLUSIONS

4.1 AM Processing of New Materials

Two new high-temperature thermoplastic materials capable of being processed on large format AM equipment were successfully demonstrated during this effort. A general approach for BAAM parameter optimization was established and should serve as a guide for printing other high temperature polymers on a large format AM machine like BAAM.

Tooling printed with PEI feedstock was shown to withstand BMI cure cycles of 190 deg C in an autoclave without significant tool movement. The epoxy phenolic tool coating identified by UDRI for sealing FDM tools was shown to be effective (i.e. stable, vacuum tight, and releasable) when properly applied to machined BAAM-printed tooling.

The PEI tooling withstood temperatures and pressures similar to those expected in RapidClave® systems without collapsing the tool, although tool flatness will need to be addressed for future trials. It will also be necessary to determine if elastic deformation of the tooling surface is occurring during the pressurization that is not detectable after the pressure is released. This could affect the dimensional tolerance of composites cured on the surface. The compatibility of AM tooling with this process will be validated on a RapidClave® system at a later date. If successful, RapidClave® type processes could easily drop cure cycles from eight hours to less than 30 minutes in aerospace applications.

The PS/CF2 tooling printed and machined similarly to the PEI tooling. Preliminary results show that the epoxy-phenolic coating bonds well to it and yields a vacuum-tight tooling surface. Future composite fabrication trials will determine the effectiveness of PS/CF2 material in aerospace composite tooling applications.

Tooling built from ABS showed promise for composite fabrication when used in conjunction with NONA epoxy resin. As indicated by the surface roughness measurements, no pitting or
erosion occurred on the tooling after the first composite cure; however, depressions of the braided carbon into the gel coat indicate that a higher service temperature gel coat may be required on future tooling. If this tooling can be validated, material costs associated with the tooling could drop by 75-85%.

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6. REFERENCES


