Lost Foam Molds Produce by Additive Manufacturing AFS Projects 19-20 #07 and #08

Marshall Lynn Miller
3D Systems, Rock Spring, Georgia, USA

Garrett Iverson
Scenic Industries LLC, Chattanooga, Tennessee, USA

ABSTRACT

Lost foam tooling is generally considered prohibitively expensive with long lead times. This is driven by the tool's design complexity, requiring extensive development utilizing machined foam patterns, and limiting it to high production volumes. Significant market opportunities for the lost foam process are available if tool costs and lead times can be reduced to be competitive with conventional processes such as automatic matchplates, high-pressure green sand equipment, and even highly-cored, chemically-bonded sand processes.

This project was conducted to support the AFS Lost Foam Division goals of expanding the marketability and viability of the Lost Foam Casting (LFC) process. The project results demonstrate that production of 3D printed LFC tools for prototypes and aftermarket operations (high mix, low volume) can also be applied to high-volume production operations. Lost foam tools developed using the additive manufacturing technologies of Powder Bed Laser, Stereolithography and Fused Deposition Modeling were shown to be competitive with conventional subtractive machining methods. To provide an accurate comparison to the known process parameters such as cycle time and pattern quality, a base existing mold design was used for all tool versions in all phases of this study.

Keywords: lost foam, casting, tooling, foundry, pattern molds, additive, subtractive, 3D, printing

INTRODUCTION

Currently, lost foam molding tools in North America are constructed of T6061-T6 billet using computer numerically-controlled (CNC) equipment that is considered expensive (over $100,000) and requires both special programming software and skilled programmers. For high mix, low-volume operations, or even medium-volume operations (a few hundred to a few thousand pieces per year), the cost of developing lost foam tooling in the United States is prohibitive compared to other foundry processes. As a result, business is frequently lost to other metalcasting processes or overseas manufacturers. For high mix, low-volume work, the traditional method is primarily machine cutting foam, which is also considered expensive.and time-consuming since subtractive machining equipment, specialized posting methods and time are required to produce cut foam. For comparison purposes, the current cost to produce the tool selected for this study was $18,000 per set and required a 3 week lead time, with conventional slotted vents manually installed. Figure 1 shows the comparative current costs and expected lead times of the various additive methods used to produce the mold.

The initial aluminum tool designs were imported into generative software and the plate thickness was reduced by 50% (Fig. 2). Structure was added to the mold reverse side for strength and theoretically to improve the conductivity of heating and cooling during the lost foam pattern molding process.

Results from the Displacement Comparison concluded that the performance of heat transfer and strength would not be impaired by the Iso-Grid design (Fig.5).

TOOL DESIGN DETAILS

- A conical perforation was added to facilitate water drainage from the ribbed area in the molding process.
- The third piece of the current tool (barrel) was incorporated into the model since additive processes can produce this feature integrally with the plate model.
- Vent slots were added to the mold models to reduce the manual effort of reinstalling them, because additive methods can accomplish venting. It should be noted that vents can be added at angles and contoured with additive methods.
- All mounting holes and locating dowels were added to the model for printing since the additive process allows it, and thus eliminated traditional machining time and tools.

The material selected for the mold was a standard aluminum alloy for 3D printing, AlSi10Mg, with a 50 micron layer height (approx. 0.002 in.). Posting was minimal with some polishing required.

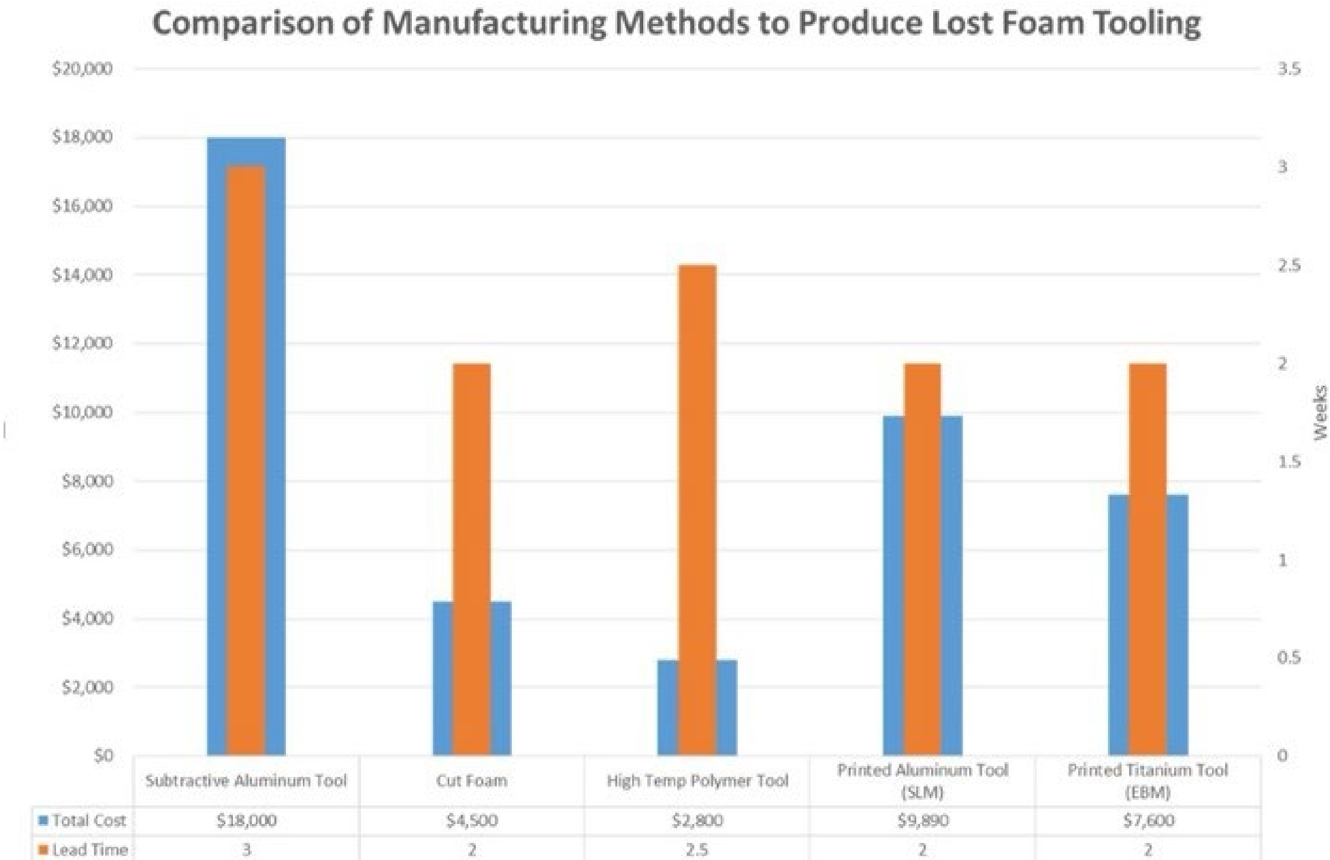

Figure 1. A graphic comparison of manufacturing costs and time to produce lost foam tooling.

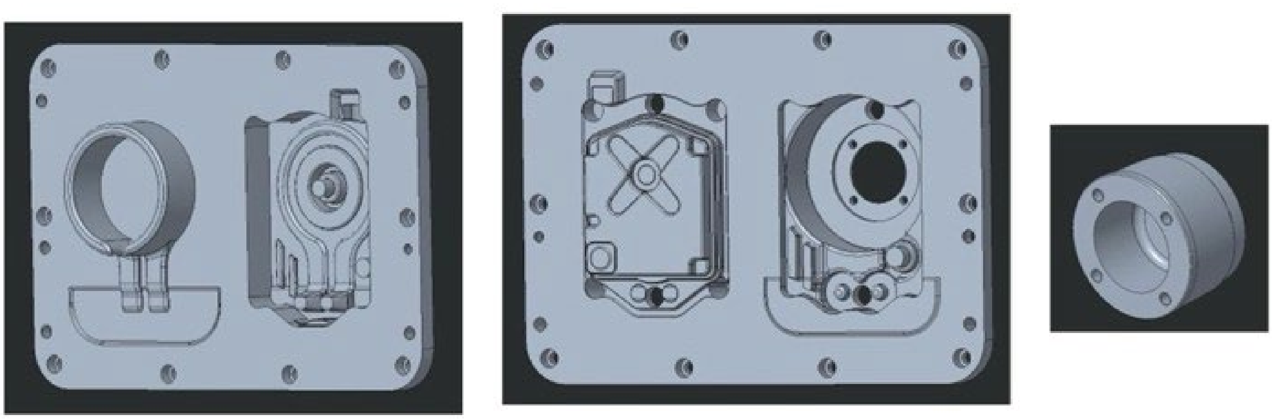

Figure 2. T h e   CAD model of the mold used in all phases of this study

STUDY DESIGN

This study was performed in 3 phases, using 3 different additive technologies and 4 additive materials:

1. PHASE 1:
   Printed Aluminum Tool—Powder Bed Laser

2. PHASE 2:
   Printed Titanium Tool—Powder Bed Laser

3. PHASE 3:
   Printed Polymer Tool—Fused Deposition Modeling (FDM)
   Printed Ceramic Tool—Stereolithography (SLA)

PHASE 1: POWDER BED LASER ALUMINUM TOOL WITH DESIGN FOR ADDITIVE MANUFACTURING (DFAM)

Figures 3, 4 and 5 provide views of the aluminum tool. Patterns produced from this aluminum tool were measured for consistency of density and permeability (Figs. 6, 7). Both were found to be consistent with traditional subtractive tool production. Cycle time was the same as the subtractive methods.

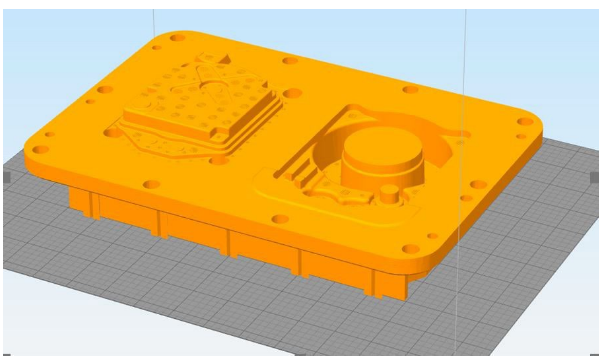

Figure 3. Top view of mold for aluminum study.

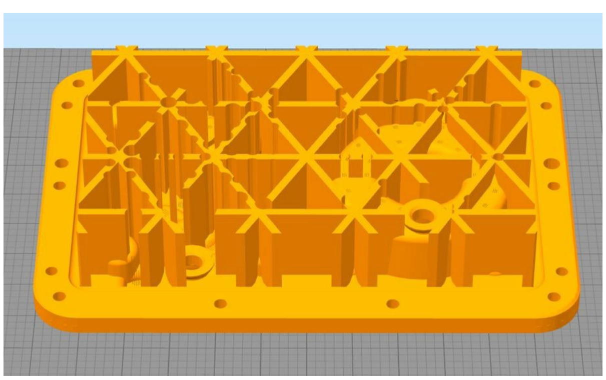

Figure 4. Bottom view of mold for aluminum study.

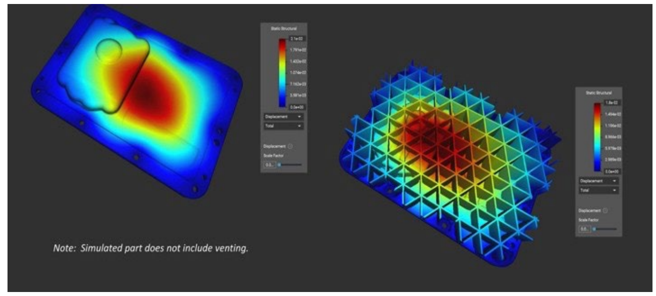

Figure 5. Displacement comparison study of aluminum model Iso-Grid design.

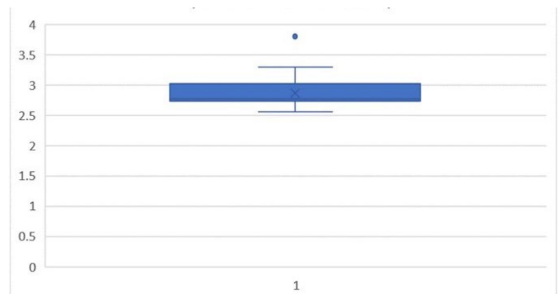

Figure 6. Pattern weight measurement of the aluminum tool (grams).

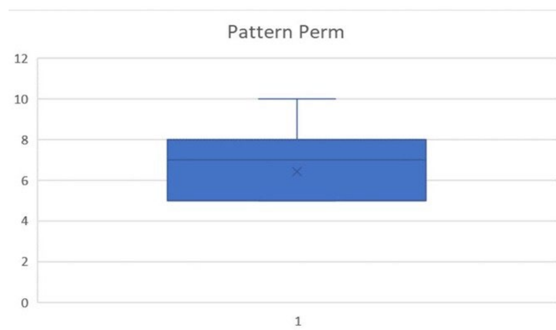

Figure 7. Pattern permeability measurement produced on the aluminum tool.

Dimensional scans were performed after molding to determine if there were any negative impacts to the mold caused by heating and cooling cycles during the molding process (Fig. 8). The dimensional variation ranged from -0.001 in. to -0.008 in.

Print time for the set was 5 days (120 hours). This is significantly less than the 3-week lead time estimate provided by the original manufacturer for the traditional subtractive method.

Faceting on the barrel was evident in the dimensional and visual inspection of the mold (Fig. 9). This is not a result of the actual printing process, but of the “fineness” setting for the exported .stl file.

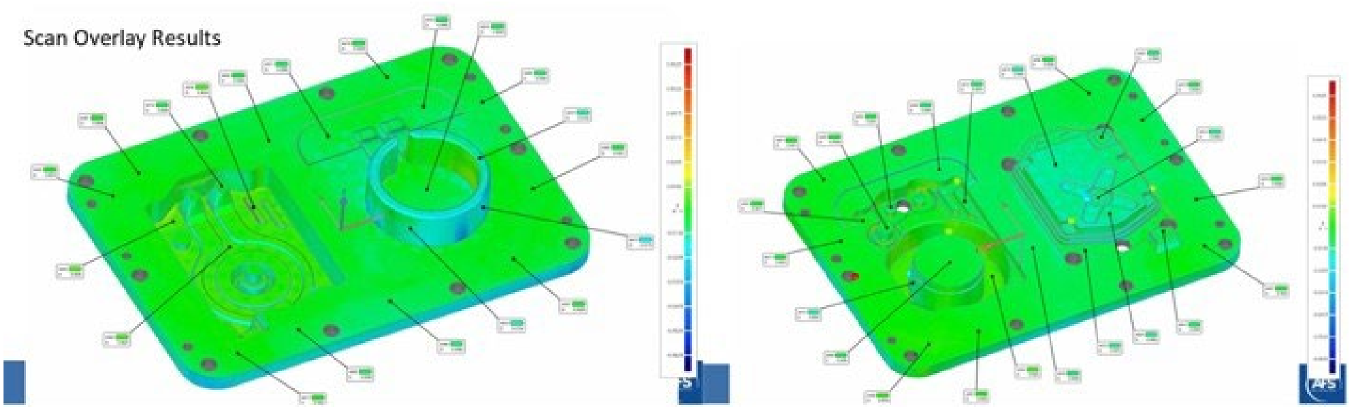

Figure 8. Dimensional scans of the aluminum tool after molding (see Appendix A for scale detail at the end of this paper).

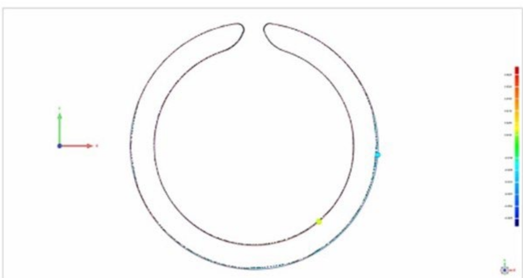

Figure 9. Barrel faceting caused by file export fineness setting.

Pattern density of 1.3 PCF (Pounds per Cubic Feet) was consistent with normal production (Figs. 6, 7). Pattern permeability was measured with a flowmeter. The flowmeter measures in an equivalent of AFS Sand Permeability numerical ratings and was captured for future reference.

Completed mold faces had venting, fill gun holes and mounting holes, all produced in the printer (Fig. 10). The venting operation is normally a manual process, and the additive process eliminated the manual labor for vent installation. Additionally, if the vents require contouring to maintain the casting shape, the vents can be printed to shape. In the standard subtractive process, the vents are first installed and then machined to the contour.

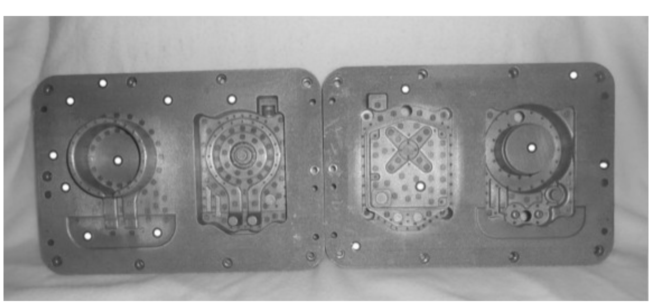

Figure 10. The aluminum mold face with vents.

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The reverse of the molds had printed structural support, as shown in Figures 11-13, to provide additional strength, since the overall mold section was reduced by 50%. It was predicted that structural support could improve heat transfer in the steaming and water flush cooling processes. Openings were added beneath the structure to allow for water drainage in the molding press. Note that the molds were mounted in the press horizontally, so only the cope pattern required water drainage in the cope position mold.

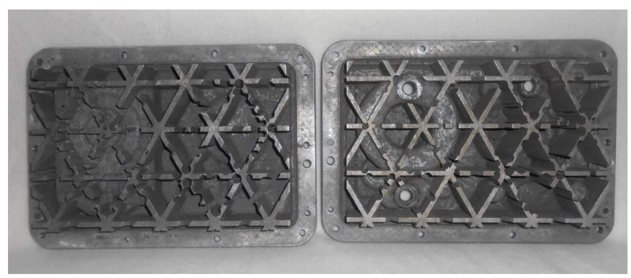

Figure 11. Aluminum mold with printed structural supports.

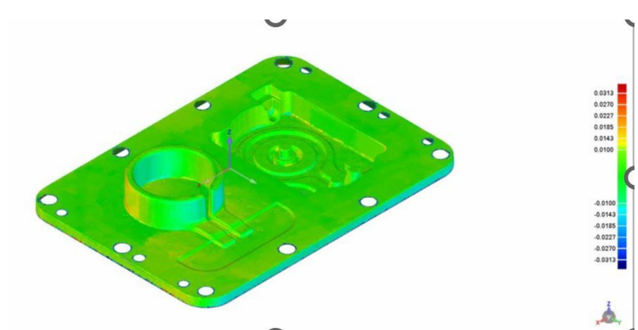

Figure 12. Lower aluminum mold with drainage and fill gun relief.

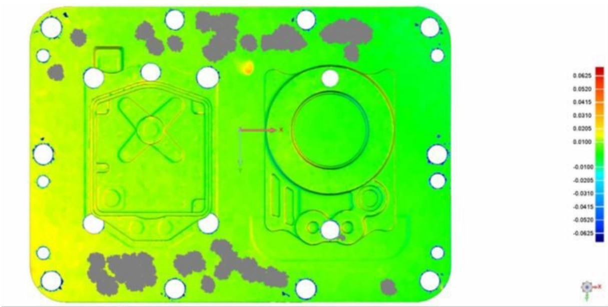

Figure 13. Upper aluminum mold with drainage and fill gun relief.

The molds were scanned after cycling to determine if any negative dimensional deviations had occurred (Figs. 14 & 15). General deviation of the lower mold plate did not exceed +/- .004 in. after molding. Barrel areas showing greater deviation that was attributed to hand polishing and smoothing to reduce faceting. Note that the contour is essentially flat after molding, indicating no warpage.

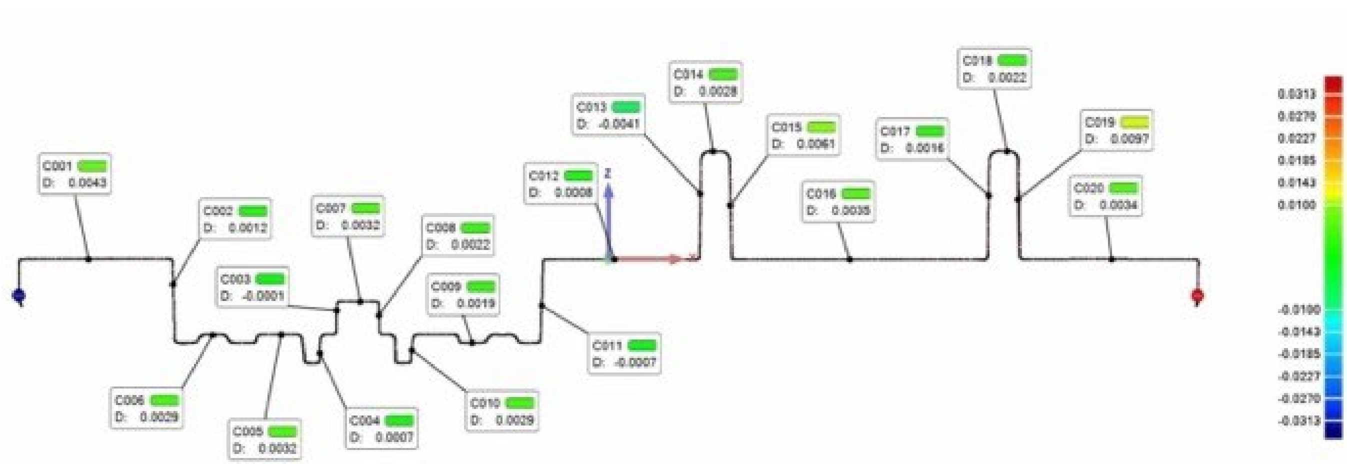

Figure 14. Contour scan of lower aluminum mold plate showing minimal dimensional variation.

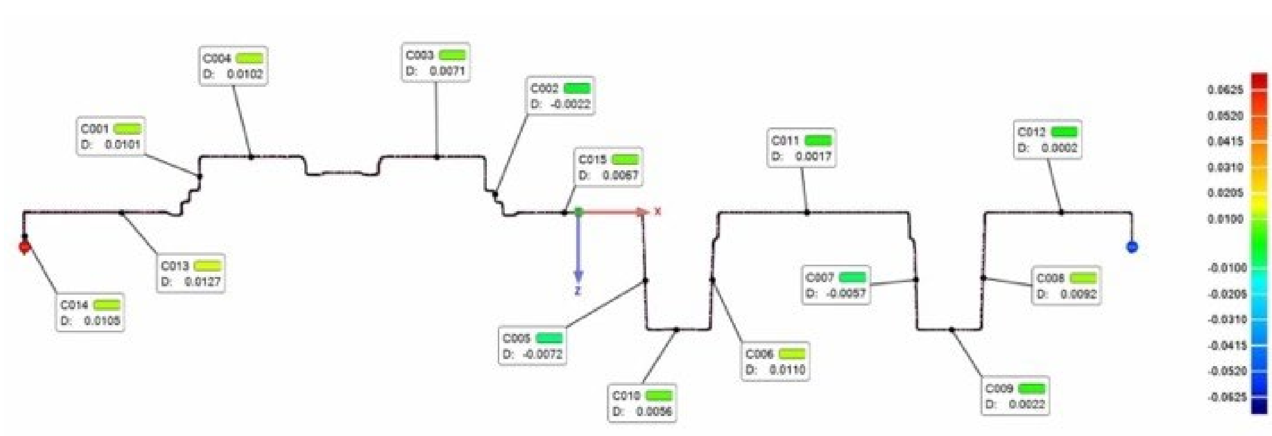

Figure 15. Contour scan of upper aluminum mold plate results showing variation of +.010" to -007."

Minor hand polishing and smoothing in the bore inner diameter (ID) and outer diameter (OD) are shown in Figures 17 and 18.

Overall views of the vents and the Direct Laser Sintering (DLS) system ability to produce fine detail vents with contour in tight areas such as the bore edge and corners are shown in Figure 17. This capability to integrally produce venting eliminated the processes of drilling, reaming and installing conventional vents.

Figure 17. Polished bore ID to reduce faceting and microvent view on the bore top edge.

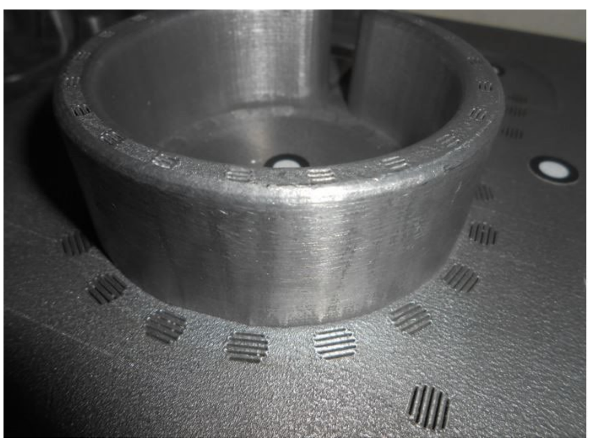

Figure 18. Polished bore OD to reduce faceting.

Restricted access locations in the mold where it is typically difficult or impossible to manually install vents were accessible with the DLS system. Conventional subtractive technology such as "side walls parallel to the direction of draw" was not utilized in this test. Figure 19 shows the ability to place vents in very tight corners and Figure 20 gives an overall view of the printed mold venting and more views of the extremely small vents integrally printed into the mold.

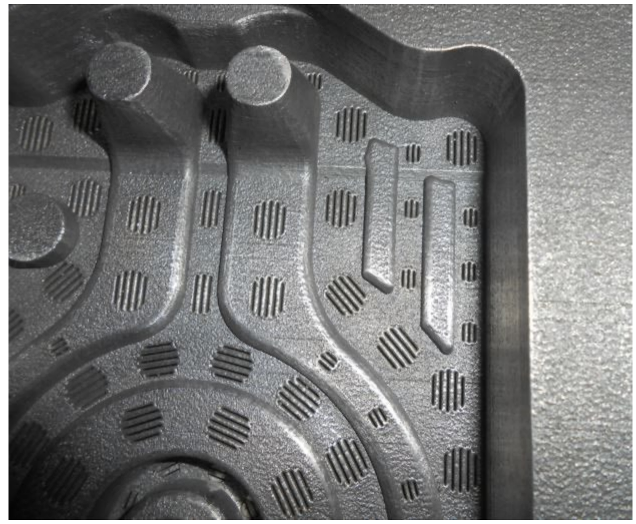

Figure 19. Installation of vents in tight corners using DLS.

Figure 20. Overall view depicting small vents in difficult locations.

Surface finish of the printed mold ranged from a Ra of 106 µm up to 460 µm with the horizontal surfaces.

Surfaces parallel with the mold plate were rougher. No problems were encountered in the molding process nor of the patterns molded. Pattern extraction proceeding normally, with a few sticking but still ejecting successfully.

PHASE 2: TITANIUM POWDER BED LASER (DFAM)

For Phase 2 of the study, Ti64 titanium powder was chosen. Because of limited build area in the DLS Printer, the upper and lower mold halves each had to be split so that they would fit the printer (Figs. 21, 22).

As done in Phase 1 (aluminum), the plate thickness was reduced by 50% to 3/8 in. The original lattice back structure was removed since it provided no heat conductivity benefit as with the aluminum mold. Since titanium (Ti) has a yield strength of >15x than that of aluminum, the thinner plate was expected to be adequately stiff. The reduction in the mold cross section allowed for faster heat transfer and cooling, enabling the Ti mold to effectively expand and cool the patterns.

Since the mold produces two final assembly halves in one mold cycle, the "split" of the mold did not require any further pattern assembly after molding. Locator male and female features were created and printed so that when placed into the molding machine bolster, the halves would interlock. As in the aluminum mold, all mounting and locator holes were printed integrally, along with the vents. After printing, a single pass cut was made around the periphery of the molds for best fit into the bolster.

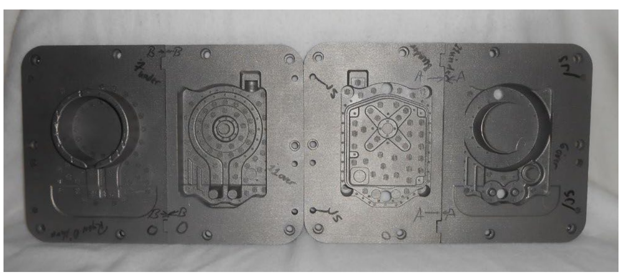

Figure 21. Front view of the Ti mold upper and lower plates.

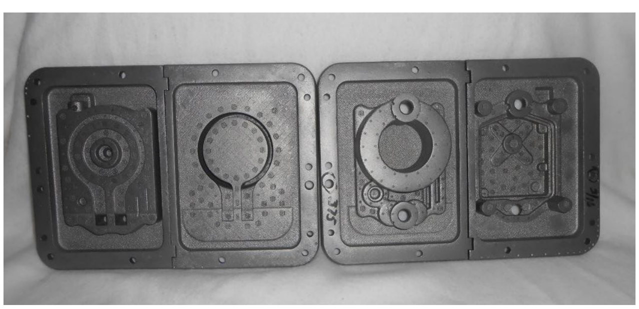

Figure 22. Back view of the Ti mold upper and lower plates.

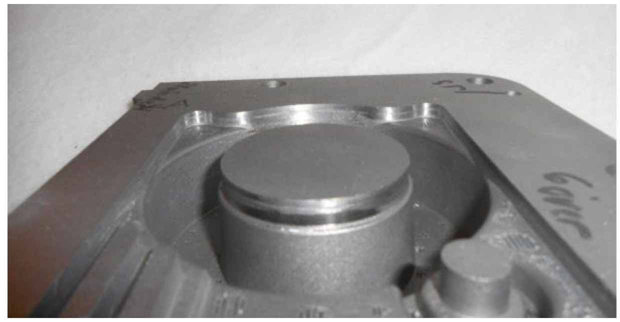

Figure 23. Titanium mold post edge polishing.

The faceting experienced in the Phase 1 (aluminum) mold barrel area was not experienced in the titanium mold since the exported .stl was set to "fine" (Fig. 23). A small print artifact is evident on the edge of the barrel that required weld repair (Fig. 24).

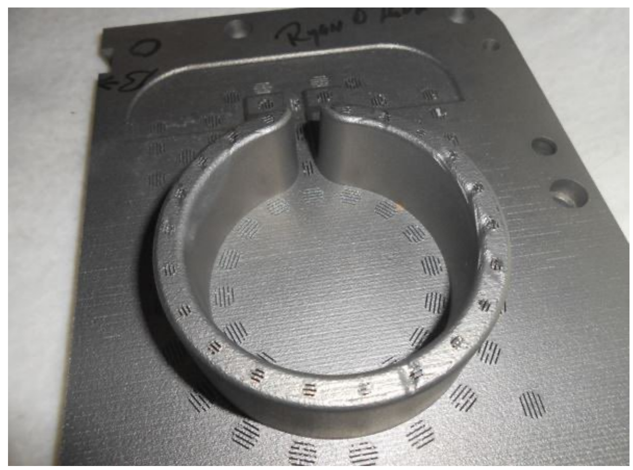

Figure 24. Print artifact on Ti mold requiring weld repair.

Along with polishing and trimming of the bore OD, some further posting was necessary as can be seen in the Figures 23 & 24. Polishing was performed at the mold face and cavity intersection to improve finish (Fig. 25). This polishing was done before installing the molds into the press.

Figures 25. Ti mold vertical wall polishing.

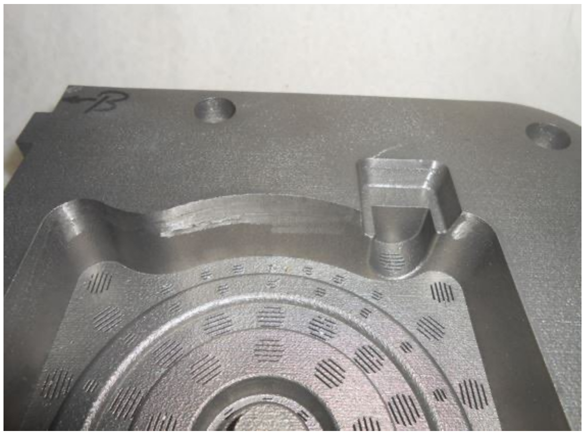

Figure 26. Vertical wall polishing on titanium mold.

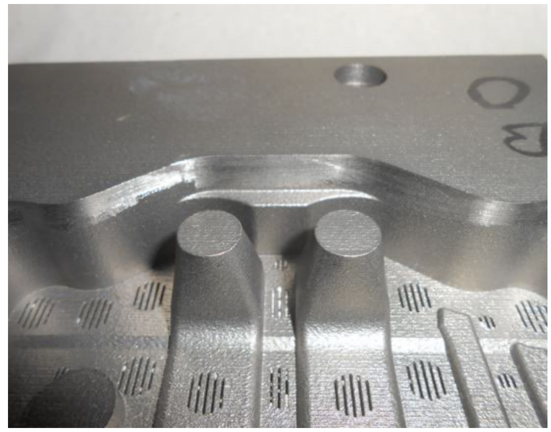

Figure 27. Vertical wall polishing on titanium mold.

Overlay scans performed after molding the upper and lower plate segments had a variation of -0.002 in. to +0.006 in. and produced acceptable patterns.

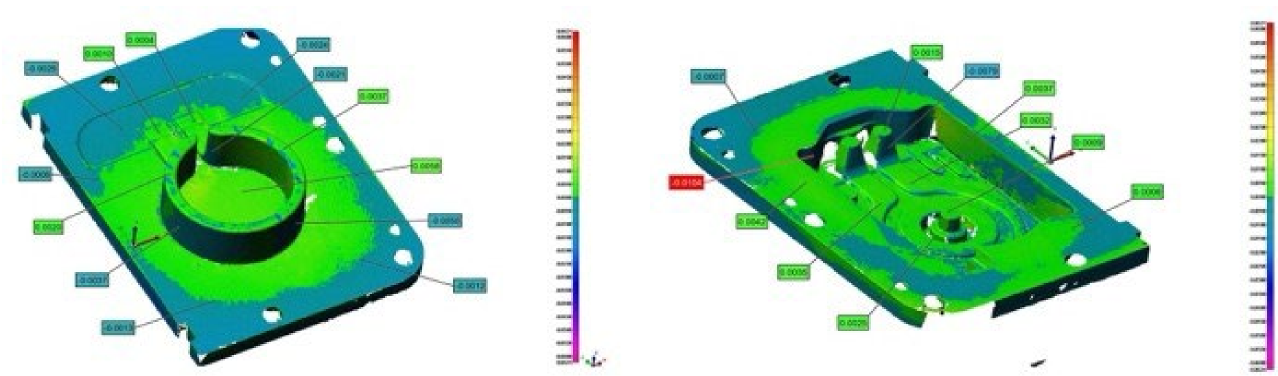

Figure 28. Upper titanium mold plate segment scan.

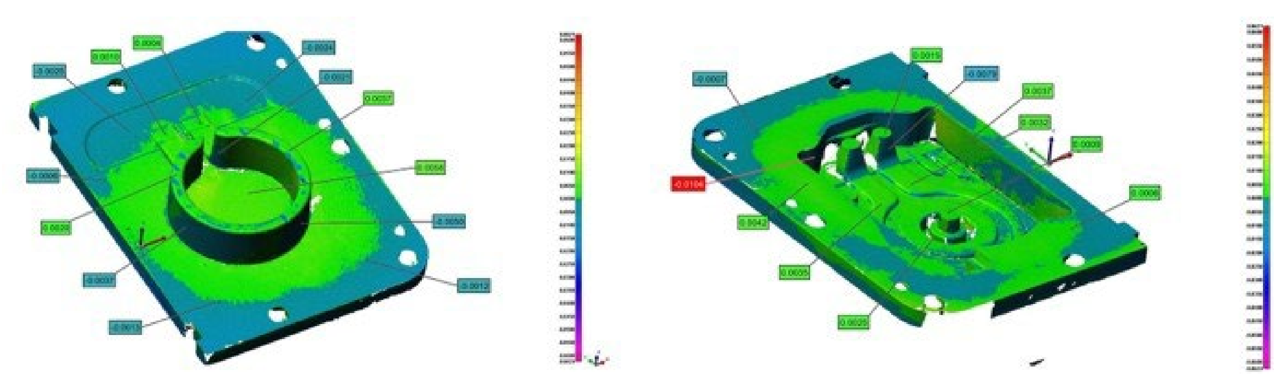

Figure 29. Lower titanium mold plate segment scan.

The patterns from the Ti mold were comparable in density and surface finish to subtractive mold patterns, with no change in cycle time. The reduced cross section and maps of the Ti tool appear to have produced similar cycle time and patterns as aluminum molds which had greater thermal conductivity (approx. 17x that of Ti).

Pattern extraction from the mold cavity was notably easy. When the mold was opened, the newly molded patterns “floated” out of the lower mold half and required no ejection or manual assistance. This was attributed to the titanium mold’s reduced expansion and contraction during heating and cooling, when compared to aluminum molds.

PHASE 3: POLYMER EXTRUSION AND SLA CERAMIC MOLD TECHNOLOGIES

This portion of the study was funded separately from the AFS contribution by Flowserve Corporation. Molds were produced by Material Extrusion Technology sometimes known as Fused Deposition Modeling (FDM) and Stereo Lithography Additive (SLA) with the following materials:

- Carbon fiber reinforced nylon polymer
- Heat-conductive nylon polymer
- Ceramic

CARBON FIBER REINFORCED NYLON POLYMER MOLDS

The first polymer mold tested was carbon fiber reinforced nylon produced with extrusion technology.

Figure 30. Back view of the FDM carbon fiber polymer mold set.

Figure 31. Front view of the FDM carbon fiber polymer mold set.

Due to the printing process limitations, vents were manually drilled and installed prior to molding. Holes for mounting and alignment in the steam chest were printed to size. In operation, patterns were produced successfully.

Less favorable outcomes included:

- Cycle time to produce the foam patterns was 2 times the normal cycle time (total of 2 min. rather than 1 min.).
- Extraction of patterns from the mold was more difficult due to the build lines that ran parallel to the parting line. No posting of the print was performed to improve finish, which may have improved pattern extraction.
- Patterns became more flexible as a result of the molding process.

While this process is workable for a limited number of cycles, this study indicates that for cycles beyond 20-30, this process may not be favorable for higher volume production operations. The FDM print proves to be a viable production method for prototype molds in reinforced nylon. Other materials that may yield better long-term results could be filled polycarbonates, Ultem, PEKK and PEEK.

Scans of the tool following molding yielded dimensional variation of approximately +0.027 in. to -0.027 in. To perform the scan overlay, the molds were mounted in a frame due to the flexibility of the post molding patterns which would mimic installation in the steam chest.

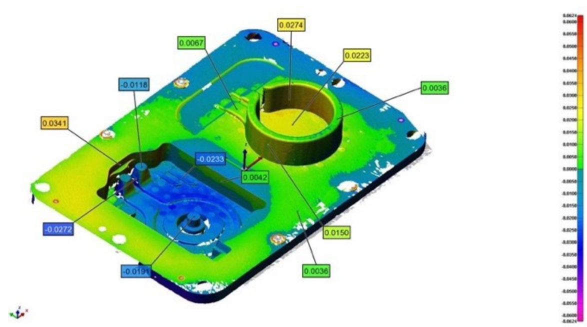

Figure 32. Scan of extruded carbon fiber reinforced nylon polymer upper mold.

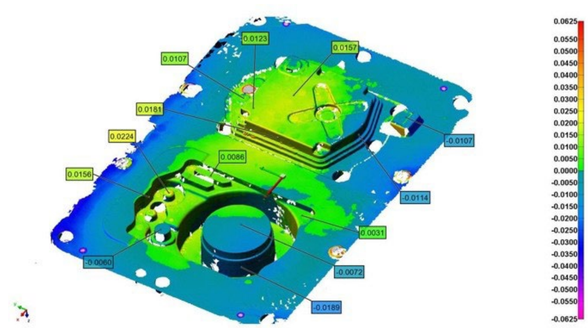

Figure 33. Scan of extruded carbon fiber reinforced nylon polymer lower mold.

HEAT-CONDUCTIVE EXTRUDED NYLON POLYMER MOLDS

The heat conductive polymer molds were producing using PEKK and nylon (Figs. 34 & 35). The purpose for using heat conductive materials was to maintain cycle time. As it was discovered in the carbon fiber reinforced nylon test, the cycle time was negatively impacted. The heat transfer properties of the conductive fill material are stated to be roughly equivalent to steel.

The PEKK molds were produced on an “open air” printer (no heated build chamber). They warped significantly in the printing process and were not usable, which was attributed to the absence of a heated bed or chamber, which can exacerbate warping.

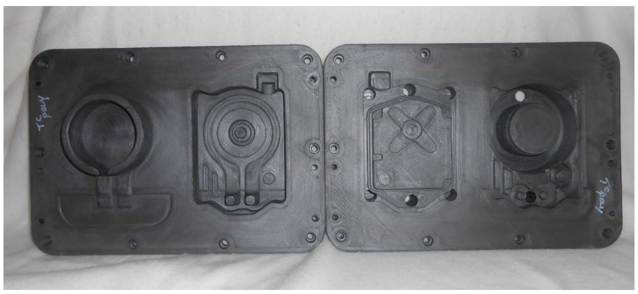

Figure 34. Front view of the PEKK mold.

Figure 35. Rear view of the PEKK mold.

Of particular interest is the capability of the FDM process to produce a “permeable” print technique—allowing a semi-solid structure that can potentially replace vents and eliminate both vent marks on the casting and vent installation time. Figure 35 shows the grid design of the mold reverse side yielding a semi-permeable working face. This allows venting in tight corners and contoured features that physical vents cannot accommodate. This technique has translated into the thermoforming process replacing aluminum and steel molds at significantly less cost.

Dimensional results of the printed molds measured within acceptable ranges. However, the molds were not delivered in time to perform the expanded tests to produce patterns. Since the molds were printed on machines without a heated bed or build area, warpage was exacerbated. If heated build chambers and beds had been used, the probability of warpage could have been reduced. It should also be noted that the nylon formulation can significantly impact warpage characteristics. In this case, the base nylon of PA-16 is not optimum for precise 3D printing.

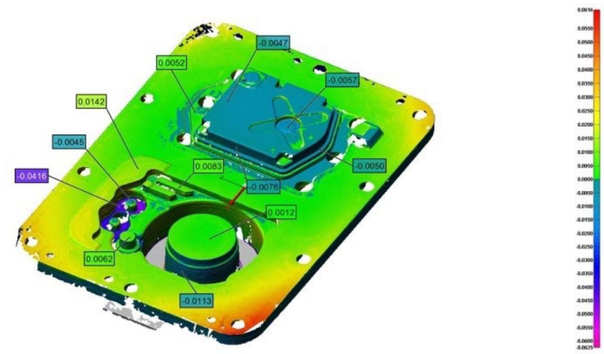

Figure 36. Dimensional scan of upper heat conductive nylon mold.

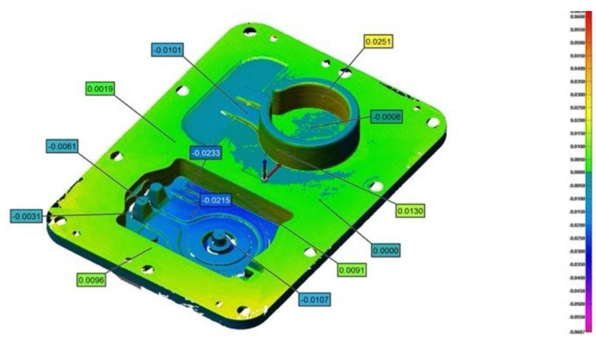

Figure 37. Dimensional scan of lower heat conductive nylon mold.

Dimensional scans showed minimal warpage of the print (Figs. 36 & 37). However, it was expected that once installed in the steam chest, the print would flatten sufficiently for purposes of determining (1) if cycle time would be impacted positively or negatively, and (2) if the permeable mold printing technique is viable in Lost Foam Pattern Molding.

CERAMIC STEREO LITHOGRAPHY ADDITIVE (SLA)

Ceramic Stereo Lithography Additive (SLA) was the final mold produced for the project. Utilizing photopolymer technology and a solution containing a ceramic material, molds were produced in the SLA Process. Molds produced were smooth, exhibiting an overall Ra surface finish of 33 µm.

The split mold printing technique (split halves) was used, the same as used in the Titanium portion of this study. This was chosen because of the SLA printer build area, requiring all vent holes, mounting holes and steam chest location holes to be printed into the mold. Slotted vents could not be printed into the molds as was done with the aluminum and titanium prints because the resolution of the SLA machine requires a slot width of 0.65 mm versus the typical vent sizing of 0.25 mm. The 0.65 mm slot is acceptable, but more cleaning of vents may be required.

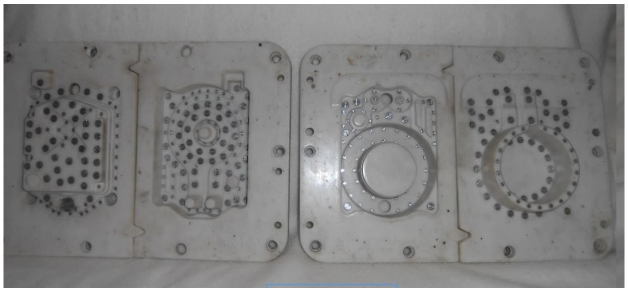

Figure 38. The ceramic mold upper segments.

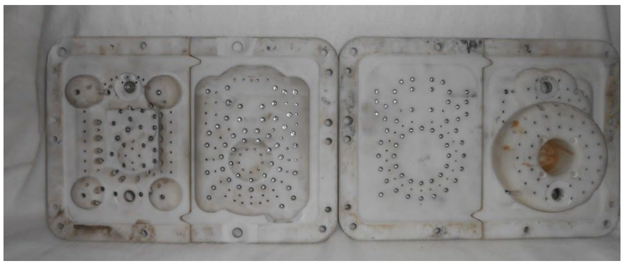

Figure 39. The ceramic mold lower segments.

Results of the ceramic SLA molding process yielded patterns exhibiting a highly smooth surface, superior to other patterns produced in this study (Figs. 38 & 39). Cycle time was not negatively impacted by the mold material.

While the ceramic SLA mold produced the best visually appearing foam pattern with a cycle time equivalent to the standard aluminum mold, dimensional variation of hole locations for mounting in the steam chest were experienced.

Because of the hole location variations and the brittleness of the material, some chipping of the mold occurred (Figs. 40, 41, 42 & 43). The chipping/fracturing were repairable with Super Glue.

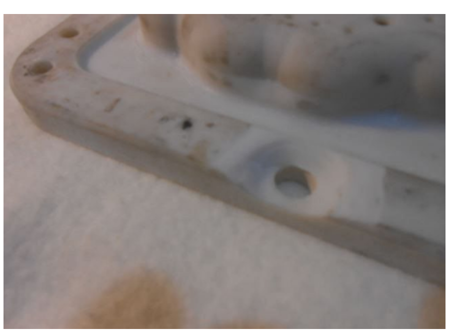

Figure 40. Chipping around the ceramic mold mounting hole.

Figure 41. Chipping around the ceramic mold mounting hole.

Figure 42. Chipping around the ceramic mold mounting hole and glue repair.

Figure 43. Chipping around the ceramic mold mounting hole and glue repair.

Peripheral adjustment of the mold fit into the steam chest was performed by grinding and attempted machining. These methods were not desirable solutions due to odor and effectiveness.

Scans of the molds found 3 of the 4 mold segments had a dimensional variation of +0.008 in. to -0.004 in. (Figs. 44, 45, 46 & 47). Two segments had a variation of +.025 in. to -0.018 in. and -.0060 in. to +0.013 in. Discussion with the supplier determined that the higher variation print was due to operator error in set up, since the dimensions of the other segments were acceptable. Stated tolerance by the supplier for the SLA Ceramic process is $\pm$ 0.00 in. for first inch, and an additional $\pm$0.0015 in.

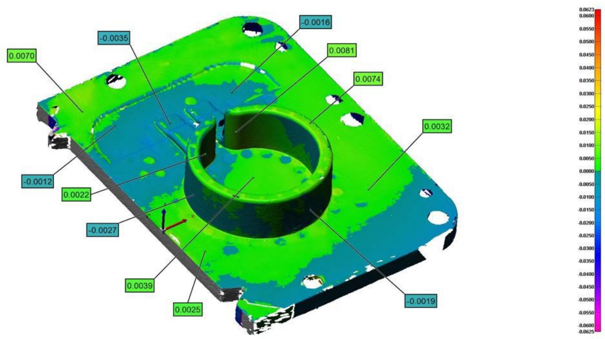

Figure 44. Scan of ceramic SLA mold upper segment 1.

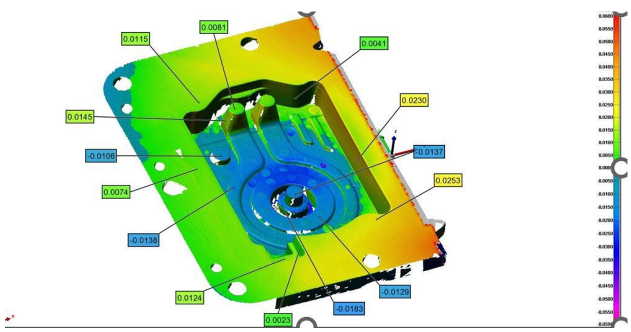

Figure 45. Scan of ceramic SLA mold upper segment 2.

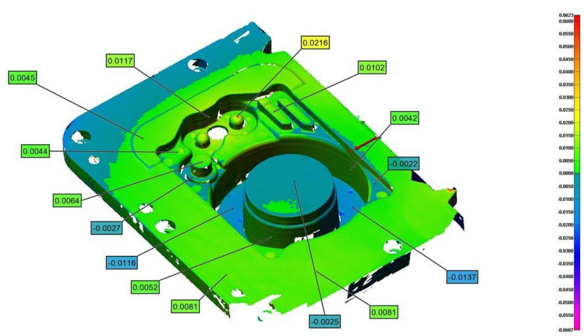

Figure 46. Scan of ceramic SLA mold lower segment 1.

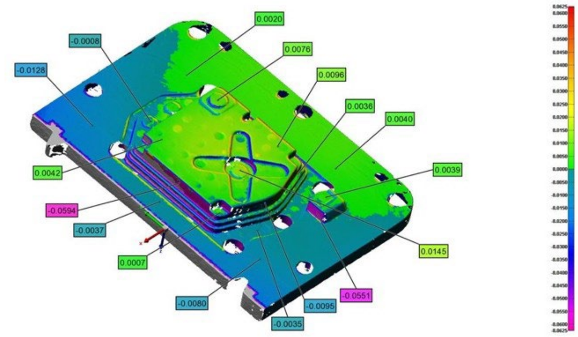

Figure 47. Scan of ceramic SLA lower upper segment 2.

Concerns included the mold cracking due to the expansion differential between of the aluminum steam chest and the ceramic material. Rubber spacers/grommets could be considered for larger ceramic mold prints in this application, which could help negate the expansion differential between the ceramic mold and the aluminum steam chest. Another alternative is production of the steam chest in a lower expansion material such as filled polymers.

SUMMARY

To rank the performance of the printed tools, and to compare to subtractive processes, the author assigned ratings to the factors of:

- Pattern finish
- Extraction
- Near net shape
- Durability
- Dimensions
- Cost
- Delivery
- Cycle time

This performance comparison is shown in Figure 48.

Projected delivery time is compared to the actual delivery times demonstrated in this study in Figure 49.

Project cost is compared to the actual cost demonstrated in this study in Figure 50.

ALUMINUM AND TITANIUM DLS TOOLS

For production molds, the Direct Laser Sintering (DLS) aluminum process proved more desirable than standard subtractive methods based on the test mold and the rankings shown in Figure 49.

Additional production time would be required to further prove this opinion.

Aluminum molds should achieve similar life results as subtractive aluminum molds. Further cycling of the molds would determine the true lifetime of printed metal tools. Titanium DLS molds should not experience the same issues as subtractive aluminum, specifically, corrosion cracking or stress cracking between vents.

Cost of the printed aluminum and titanium (DLS) molds can be further reduced in a production facility that is not restricted on recycling powder. Aerospace and medical requirements that restrict powder recycling can be stringent since recycled powder can cause print defects. But for producing commercial products, powder recycling could be increased since minor imperfections may be acceptable or can be repaired with welding.

Aluminum and titanium DLS molds allowed for improved mold venting since the additive process allows for printing contoured vents in tight areas and thinner sections, eliminating manual vent installation. This study also demonstrated that thinner cross sections do not appear to have a positive or negative impact on foam pattern molding.

CERAMIC SLA AND POLYMER FDM TOOLS

This study indicated that ceramic Stereo Lithography Additive (SLA) and polymer Fused Deposition Modeling (FDM) tools are viable and the best choice for short run prototypes.

Ceramic is inexpensive and fast, has no expansion or contraction, and produces a high- quality finish. Polymer is even less expensive, and like ceramic, faster than subtractive methods.

Other more durable polymers such as PPSF, PEKK, etc. can substitute for cut foams and lower production volumes based on their material properties alone.

Additionally, since the initiation of this project, extrusion technology has advanced to the point that highly durable polymers, filled with carbon fiber or glass fiber, can be produced with pellet extrusion and machined to size. Heat conductive polymers are also available to help improve cycle when deemed necessary. Formulation of the conductive polymers can be adjusted to improve warpage issues.

Since the completion of this study, new polymer materials have become available, and this study indicates that these new materials should be tested.

SLA ceramic may be viable for low- to medium- volume production.

Verified builds for dimensional control of the prints and addressing the causes of fracturing or potential fracturing will allow this method to move forward as it is extremely competitive and produces foam patterns with a high quality surface finish.

All of the methods used in this study were successful in making foam patterns. From a cost standpoint, all techniques were the same as or less than conventional subtractive methods, with reduced labor and materials costs.

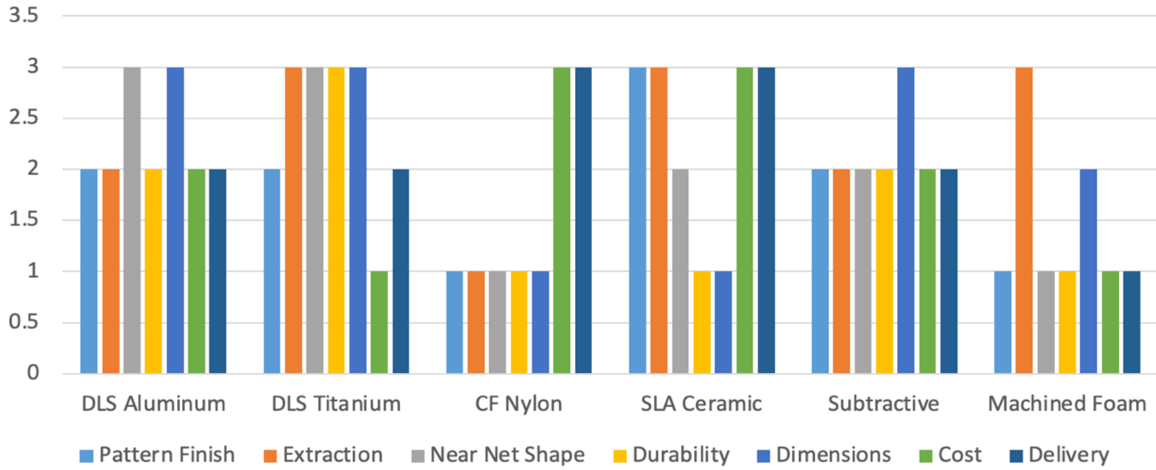

Figure 48. Performance factor rankings of printed tools by process and material.

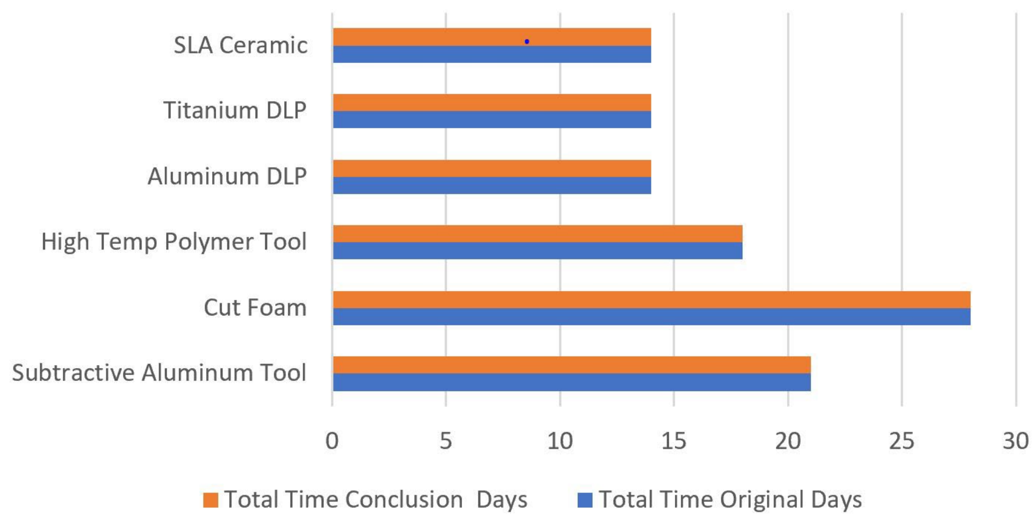

Figure 49. Projected mold delivery time compared to actual delivery time.

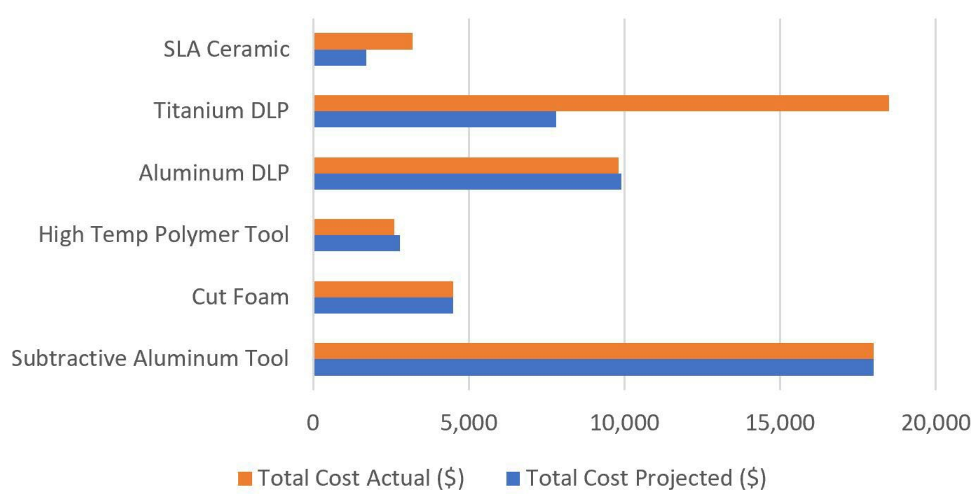

Figure 50. Projected mold cost compared to actual cost.

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APPENDIX A

Scale detail for dimensional scans presented in Figure 8.