

ORNL/TM-2019/1228
CRADA/ NFE-17-06683

Additive Manufacturing of Polyurethane Foam Mold Tooling



CRADA FINAL REPORT
NFE-17-06683

Approved for Public Release.
Distribution is Unlimited.

Dr. Brian K. Post
Alex Roschli
Phillip Chesser
Breanna Rhyne
Celeste Atkins
Matthew Sallas
Nikolas Tsiamis

February 28, 2019

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via US Department of Energy (DOE) SciTech Connect.

Website <http://www.osti.gov/scitech/>

Reports produced before January 1, 1996, may be purchased by members of the public from the following source:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.gov
Website <http://www.ntis.gov/help/ordermethods.aspx>

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange representatives, and International Nuclear Information System representatives from the following source:

Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@osti.gov
Website <http://www.osti.gov/contact.html>

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Energy & Transportation Science Division
Advanced Manufacturing Office

Additive Manufacturing of Polyurethane Foam Mold Tooling

Authors
Dr. Brian K. Post
Alex Roschli
Phillip Chesser
Breanna Rhyne
Celeste Atkins
Matthew Sallas
Nikolas Tsiamis

Date Published:
February 28, 2019

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Approved For Public Release

CONTENTS

	Page
Contents.....	iii
List of Figures.....	v
Acknowledgements	vi
Abstract.....	1
1. Additive Manufacturing of Polyurethane Foam Mold Tooling.....	1
1.1 Background.....	1
1.2 Technical Results	2
1.2.1 Task 1 – Long-Term Durability.....	3
1.2.2 Task 2 – Proof of Concept for Watertight Operation	3
1.2.3 Task 3 – Define the material trade-offs for speed, resolution, and material performance	8
1.2.4 Task 4 – New foam tool design to leverage new technology	8
1.3 Impacts.....	9
1.3.1 Subject Inventions	10
1.4 Conclusions.....	10
2. Whirlpool Background	12

LIST OF FIGURES

Figure 1. Production Freezer Door Foaming Mold	1
Figure 2. BAAM Produced Freezer Door Foaming Mold.....	2
Figure 3. Manufactured Freezer Door from AM Tool	2
Figure 4. Whirlpool Ice-maker Door Tool	3
Figure 5. Amana Door Foam Tool with Flow Channels	4
Figure 6. Leak Testing Apparatus	4
Figure 7. Leakage Failures	4
Figure 8. Approach #2: Embedded Copper Tubing.....	5
Figure 9. Manufacturing Process.....	6
Figure 10. Thermal Imaging of the Copper Inlayed Door Tool	6
Figure 11. Mold for Thermoset Resin Tool.....	7
Figure 12. Heat Exchangers Installed in Mold	7
Figure 13. Thermal Measurement of the Cast Epoxy Tool.....	8
Figure 14. Mid-scale Printed Tool for Amana Refrigerator Door.....	9
Figure 15. Mid-scale Printed High Thermal Conductivity Tool for Amana Refrigerator Door	10

ACKNOWLEDGEMENTS

This CRADA NFE-17-06683 was conducted as a Technical Collaboration project within the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) sponsored by the US Department of Energy Advanced Manufacturing Office (CPS Agreement Number 24761). Opportunities for MDF technical collaborations are listed in the announcement “Manufacturing Demonstration Facility Technology Collaborations for US Manufacturers in Advanced Manufacturing and Materials Technologies” posted at <http://web.ornl.gov/sci/manufacturing/docs/FBO-ORNL-MDF-2013-2.pdf>. The goal of technical collaborations is to engage industry partners to participate in short-term, collaborative projects within the Manufacturing Demonstration Facility (MDF) to assess applicability and of new energy efficient manufacturing technologies. Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

ABSTRACT

In this DOE AMO Technical Collaboration (MDF-TC-2017-078), ORNL partnered with Whirlpool Corporation. to develop low-cost prototype tooling for the manufacturing of refrigerators. Techniques for producing watertight and high thermal-conductivity tools were developed and evaluated. In addition, additive manufacturing systems at multiple volume and resolution scales were evaluated for performance, resolution, and cost for the intended application.

1. ADDITIVE MANUFACTURING OF POLYURETHANE FOAM MOLD TOOLING

This phase two ORNL Manufacturing Demonstration Facility (MDF) technical collaboration project (MDF-TC-2017-078) began on April 12, 2017 and was completed on February 28, 2019. The collaboration partner, Whirlpool Corporation, is a large business. In this project, several new approaches were developed and tested for producing functional tools for refrigerator manufacturing. Paths to commercial systems capable of addressing the needs of the appliance industry were investigated and ultimately, low-cost solutions for both systems and materials were determined.

1.1 BACKGROUND

Whirlpool is the industry leader in the manufacturing and marketing of home appliances. The primary objective of the technical collaboration between ORNL and Whirlpool was to leverage the new ORNL additive manufacturing process and materials into a long term, quick change tooling concept to drastically reduce product lead and development timelines as well as costs.

Phase 1 of the collaboration was conducted under CRADA NFE-15-05744 from August 1, 2015 through July 29, 2016. Phase 1 successfully demonstrated the ability to produce low cost tooling for limited production trials for Whirlpool's refrigerator manufacturing facility's cabinet foaming line, using the Big Area Additive Manufacturing (BAAM) and Cosine Medium Area Additive Manufacturing (MAAM) processes.

Under Phase 1, three ORNL printed tools (Figure 1) were trialed at Whirlpool's production facility in Amana, Iowa, in July 2016. The tools replaced the production line tools on the refrigeration foaming production line. Each tool was used to make three freezer doors on the production line (Figure 2), for a total of 9 doors, and all were completed successfully with no apparent wear to the tools. The results of Phase 1 demonstrated a production method capable of developing low cost, short turn tooling in as little as one day per mold set.



Figure 1. Production Freezer Door Foaming Mold

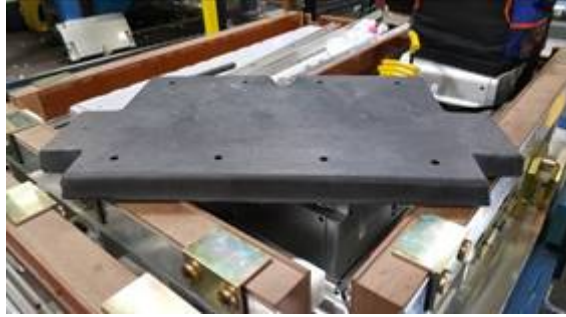


Figure 2. BAAM Produced Freezer Door Foaming Mold



Figure 3. Manufactured Freezer Door from AM Tool

The goal of Phase 2 of the project was to leverage new designs and tooling innovations in the application of the technology to a new model line. The target was to parallel construction of a set of foam molds based on current best practice aluminum designs. These models include the ability to heat and cool the mold tools with forced convection with 50psi water from a thermolator.

Foam mold supports are critical for reliable, accurate production of refrigerators. However, current foam mold supports are complicated, time-consuming, expensive, and maladaptive. In Phase 1 of this project, Whirlpool and ORNL were successful in creating common fixture cores and providing lightweight, easily adaptable fixture sections.

In Phase 2, ORNL aimed to test and improve the Phase 1 foam molds in several ways. First, the long-term durability of the molds was tested. Then, the watertight concept to allow heating and cooling of the molds was tested. ORNL worked to define the foam molds' material trade-off curves for speed, resolution, and material performance. Additionally, ORNL built parallel foaming molds for new and existing products.

1.2 TECHNICAL RESULTS

The target of Phase2 focused on the needs outlined by Whirlpool, based on the results of Phase I, namely: durability testing, high thermal conductivity and the ability to heat and cool the molds to ensure product consistency over long production runs.

Phase 2 of this technical collaboration consisted of seven tasks. Task 1 was to test the long-term durability of the foam molds. Task 2 was a proof-of-concept for watertight operation. Task 3 was to define the material trade-offs for speed, resolution, and material performance. Task 4 was to investigate building foam molds for new and existing products. Task 5 was to explore new foam tool design to leverage new technology and materials. Task 6 was to improve partnership with machine manufacturers and foam tool designers.

1.2.1 Task 1 – Long-Term Durability

In 2017, the tools made at ORNL were used in a Whirlpool production line at their production plant in Amana, Iowa, to make 10 refrigerator doors each, and the CMM data was collected to confirm dimensional accuracy. Unfortunately, due to production schedule changes, the model of refrigerator that the tools were designed for was taken out of production, and the durability testing is awaiting the restart of that product line in the production facility. In addition, to address the issues in production at the Amana facility, a second tool (Figure 4) was identified as an ice maker door tool for an Ohio plant.

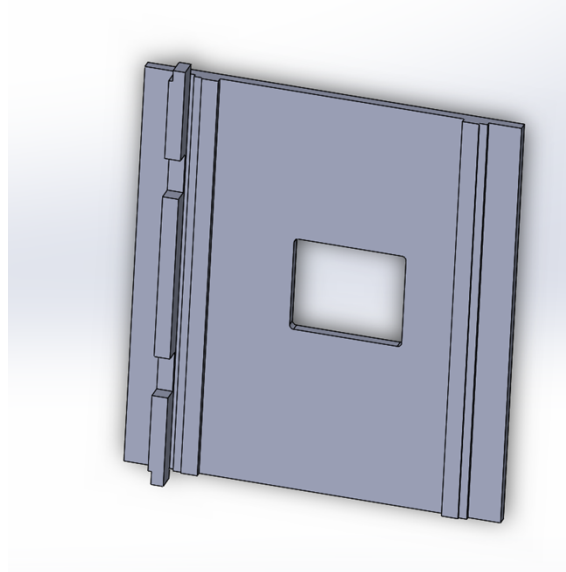


Figure 4. Whirlpool Ice-maker Door Tool

ORNL produced one of the tools from a reverse-engineered model of the existing tool, printed a replica, machined and delivered it to the factory. The engineers at the plant struggled installing and testing the tool without crushing the corners of the liners. Therefore, at the end of project, durability testing is still awaiting the restart of the Amana production.

1.2.2 Task 2 – Proof of Concept for Watertight Operation

To meet the objective of creating full cabinet molds suitable for production volume tooling, a methodology for routing 50psi water through the tools needed to be determined. In production, water conditioned by a thermolator is used to either heat or cool the tools in order to achieve the desired setpoint (around 100 degrees Fahrenheit).

Most fused deposition polymer printers are incapable of producing watertight components because of the voids left between beads of material. Because of the bead geometry and material extrusion pressures of the BAAM process, it has been determined that water-tight components can be successfully printed for constrained geometries. The first successful watertight tool was designed to have a serpentine path through the polymer tool for the fluid, as shown in Figure 5.

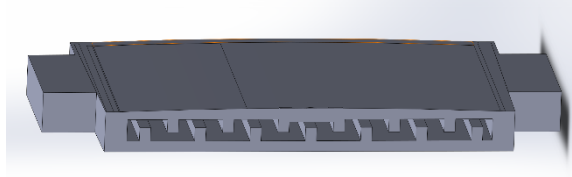


Figure 5. Amana Door Foam Tool with Flow Channels

This part was fabricated and tested using the experimental apparatus shown in Figure 6. Using a regulated commercial water supply of 50psi, water was forced into the part, compressing the trapped air which resulted in a corresponding pressure reading on the flow exit. In the worst case scenario of blocked flow, the tool could see the full 50psi in production, so the tool must be capable of withstanding >50psi in order to be considered successful.



Figure 6. Leak Testing Apparatus

At low pressures, the first tools exhibited leaks at the top surfaces of the tool due to macro-scale voids in the solid fill layers. This type of leakage is shown Figure 7a.



Figure 7. Leakage Failures

In subsequent trials, this leakage phenomenon was eliminated through toolpath modifications to ensure these macro voids were staggered on subsequent layers to avoid leakage paths, and also through parameter adjustments to ensure complete profile fill.

The second form of leakage observed were interlaminar failures at higher pressures (20-30psi). These leaks, as shown in Figure 7b, were initiated between layers caused by pressure forces overcoming the inter-laminar bond strength of the printed component. These failures were typically accompanied by an audible cracking noise and, once initiated, the leaks were permanent, even at lower pressures. As a result, this methodology was deemed unsatisfactory for the application unless new materials with better interlaminar strength can be determined.

A second approach was developed wherein copper tubing was inserted into a thin shell door foam tool, as shown in Figure 8. The back side of the shell is insulated with expanding foam to prevent heat loss to non-critical surfaces. Water flows through the tube in the mold and conducts to the surface of the tool.

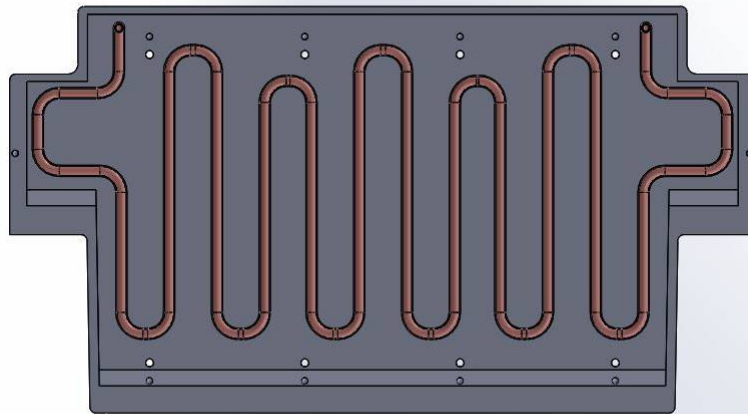


Figure 8. Approach #2: Embedded Copper Tubing

Pictures of the fabrication of one of these tools are shown in Figure 9. Note that the copper tubing is fabricated using a mandrel and bonded to the machined groove in the machined part.

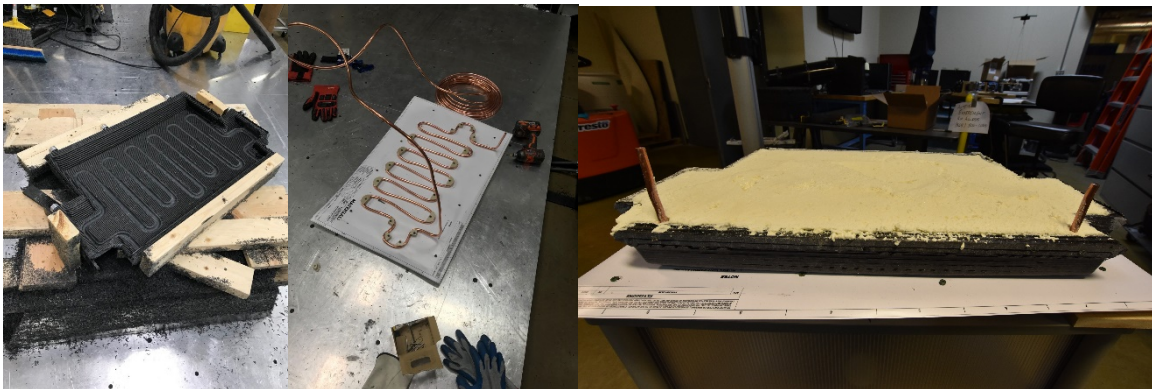


Figure 9. Manufacturing Process

This process results in a watertight part capable of supporting the 50psi thermolator pressure.

Whirlpool tested these tools for their thermal conductivity by attaching a thermolator and measuring the surface temperature profile with a thermal camera.

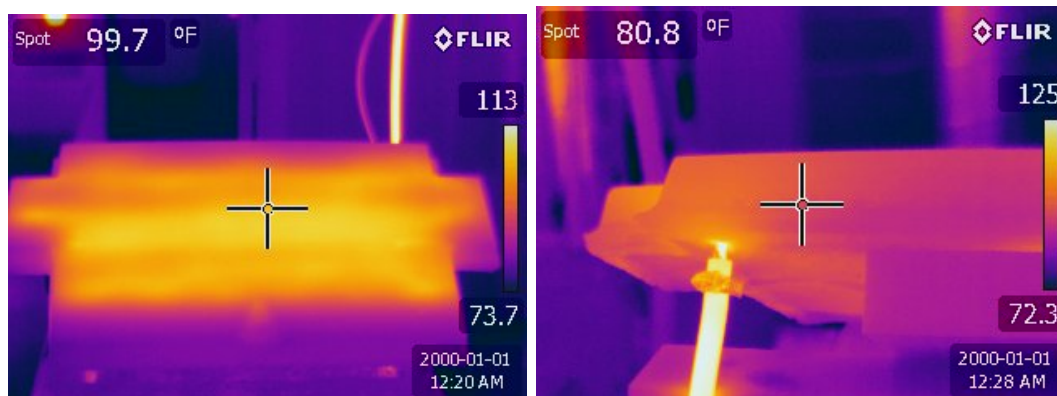


Figure 10. Thermal Imaging of the Copper Inlaid Door Tool

While the tool was functional and better than the original tools developed in Phase 1 of the project, the limited thermal conductivity of thermoplastic materials significantly hindered the thermal performance of the tools, as illustrated in Figure 10. With a setpoint of 125 degrees Fahrenheit, the tool surface only reached 100 degrees at its warmest point, and towards the edges this significantly dropped to 80 degrees. Thermoplastic resin systems generally have thermal conductivity coefficients of 0.1-0.5W/mK. Therefore, most printable polymers would perform similarly.

In order to improve the thermal conductivity of the tools, the decision was made to cast a high thermal conductivity ($\sim 10\text{W/mK}$) epoxy tool from a BAAM printed mold. Figure 11 shows the printed and machined mold. Ceramacast 673-N, a highly filled (with Silicon Carbide) resin from Aremco, was chosen based on the thermal conductivity requirements.

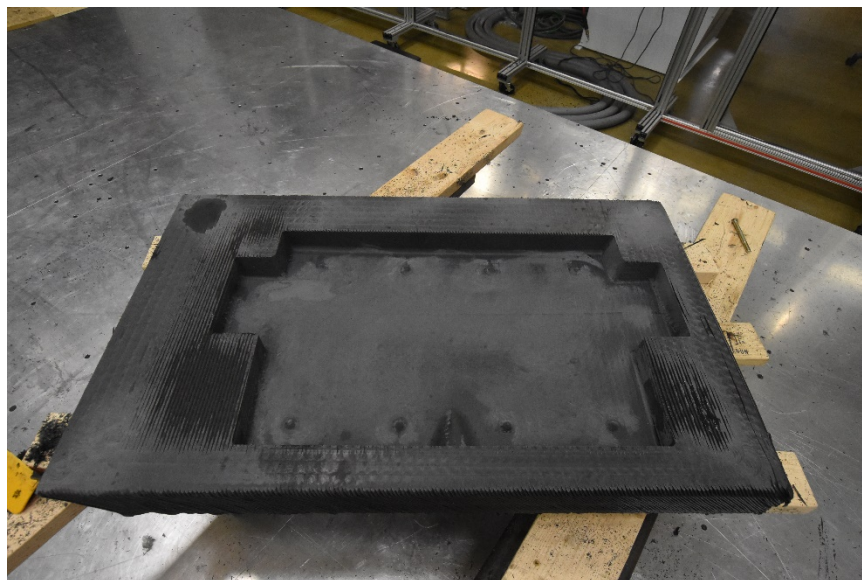


Figure 11. Mold for Thermoset Resin Tool

Heat exchangers, which are commercially available transmission coolers, were installed in a printed frame within the mold, as shown in Figure 12. Epoxy was poured into the mold to fully encapsulate the heat exchangers.

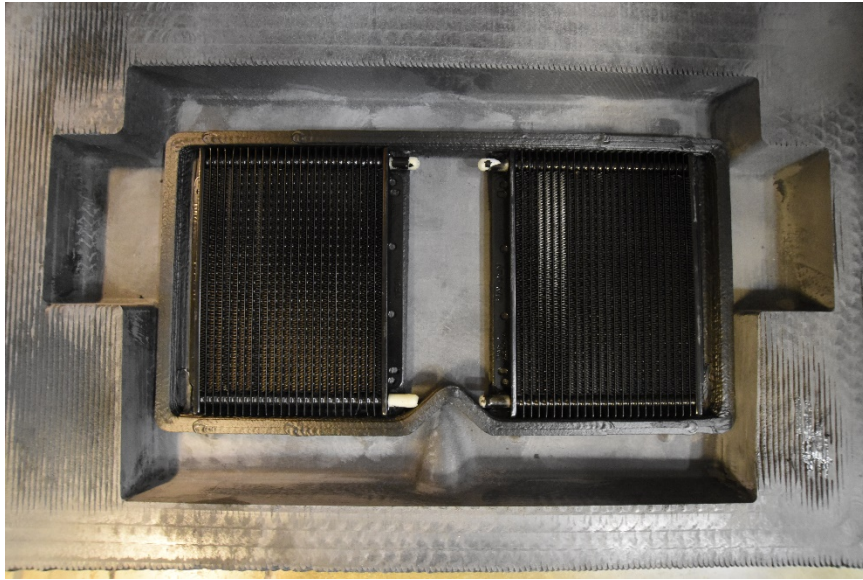


Figure 12. Heat Exchangers Installed in Mold

Relative to the previous iteration, the thermal performance of the fabricated tool was greatly improved, as demonstrated in Figure 13.

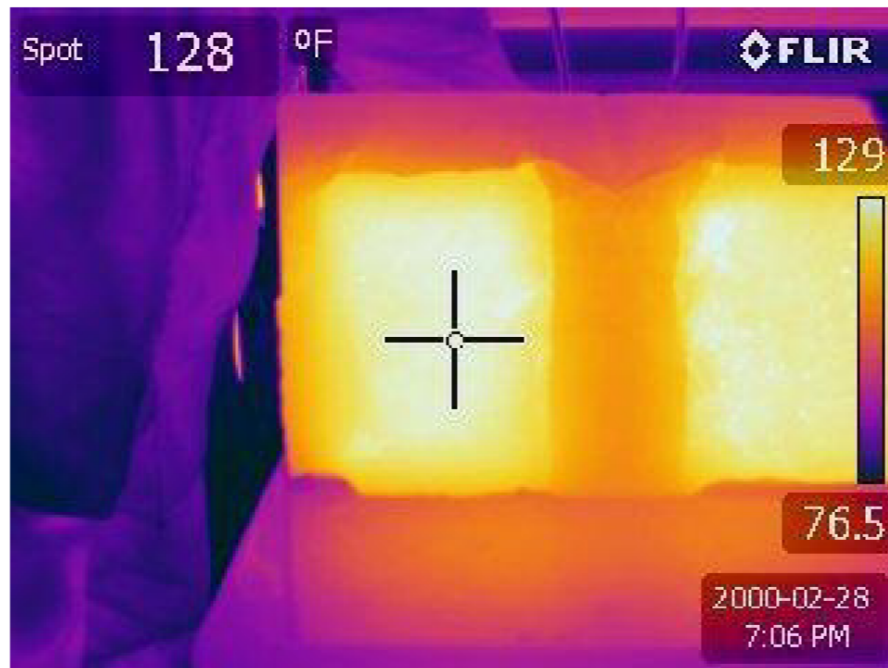


Figure 13. Thermal Measurement of the Cast Epoxy Tool

While the thermal conductivity improvements were significant, the brittleness of the ceramacast resin caused fractures during the demolding process that ultimately would make the tool too fragile to use in the production environment.

1.2.3 Task 3 – Define the material trade-offs for speed, resolution, and material performance

In order to meet the demands of the application, the primary targets were resolution and material performance. It was determined through Task 2 that the minimum thermal conductivity necessary is $>5\text{W/mK}$. Most thermoplastics are much lower, around 0.1W/mK . The trade-off for using thermoplastic tools ultimately falls on the end use application. There exists a subset of refrigeration foam tools that are not heated. For those applications, the polymer tools perform adequately and the lead times available through AM are much better than traditional tooling routes. Therefore, for prototype tooling, AM polymer tools work and provide a significant value proposition.

The second tradeoff of speed vs resolution reduces to amount of postprocessing necessary to achieve a functional tool. It was determined that parts produced on high resolution 3D printers could be used without any post processing. However, the maximum build size, material cost, and build rates limit the utility of these systems to create tools for this application. The BAAM or other similarly sized printers are much too large and print at too low a resolution to ultimately be applicable to the appliance industry. Through this project it was identified that a midscale system with sub 1mm nozzle sizes and deposition rates $>5\text{lb}$ per hour would be ideal and require no postprocessing.

1.2.4 Task 4 – New foam tool design to leverage new technology

During the execution of this research program, many new “midscale” polymer AM systems were released. Two of these were used to produce tools for refrigerator foam injection.

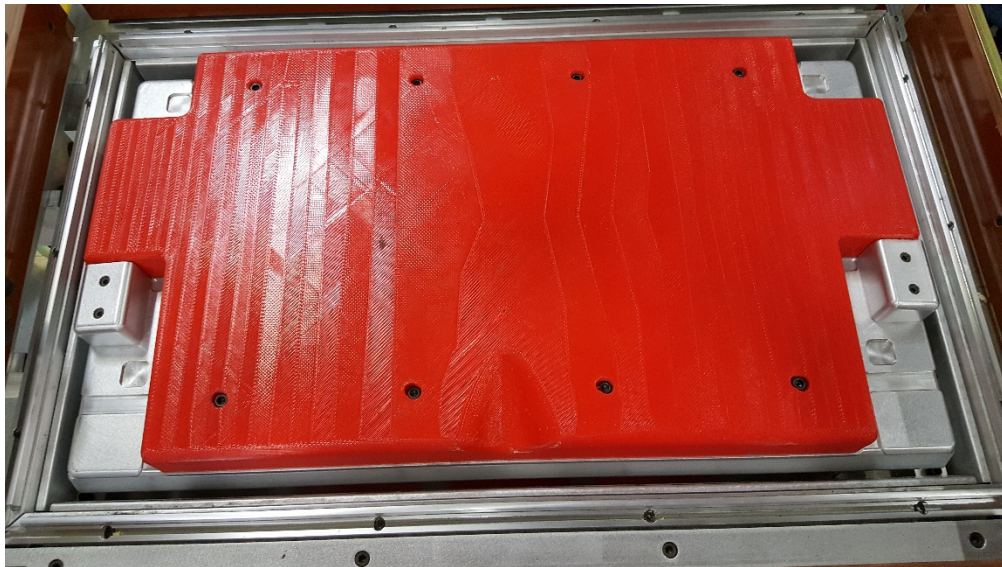


Figure 14. Mid-scale Printed Tool for Amana Refrigerator Door

The tool shown in Figure 14 was printed on a Cosine AM1 using 3mm filament with a print time around 20hrs. This tool was tested successfully at the Amana production facility. The resolution was high enough that, without any post processing, the stair-stepping in the tool surface was not transferred to the liner during the foaming process. However, the shrinkage noticed in the tool after print was too high to produce an in-spec refrigerator door.

To address the thermal conductivity challenges, a new tool was produced using the 3D Platform 400 Series printer which operates on 6mm filament. To improve thermal conductivity, a new material was used: Ice9 Flex from TCPoly. Ice9 Flex is a thermally conductive non-insulating plastic that TCPoly developed and made into pellets which we were able to extrude into 6mm filament to feed into the 3DP system. This material has a max thermal conductivity of $8 \frac{W}{mK}$, which is 8000% greater than the ABS. Printing the mold took approximately 20hrs. Below is an image of the mold after vapor smoothing the top surface.

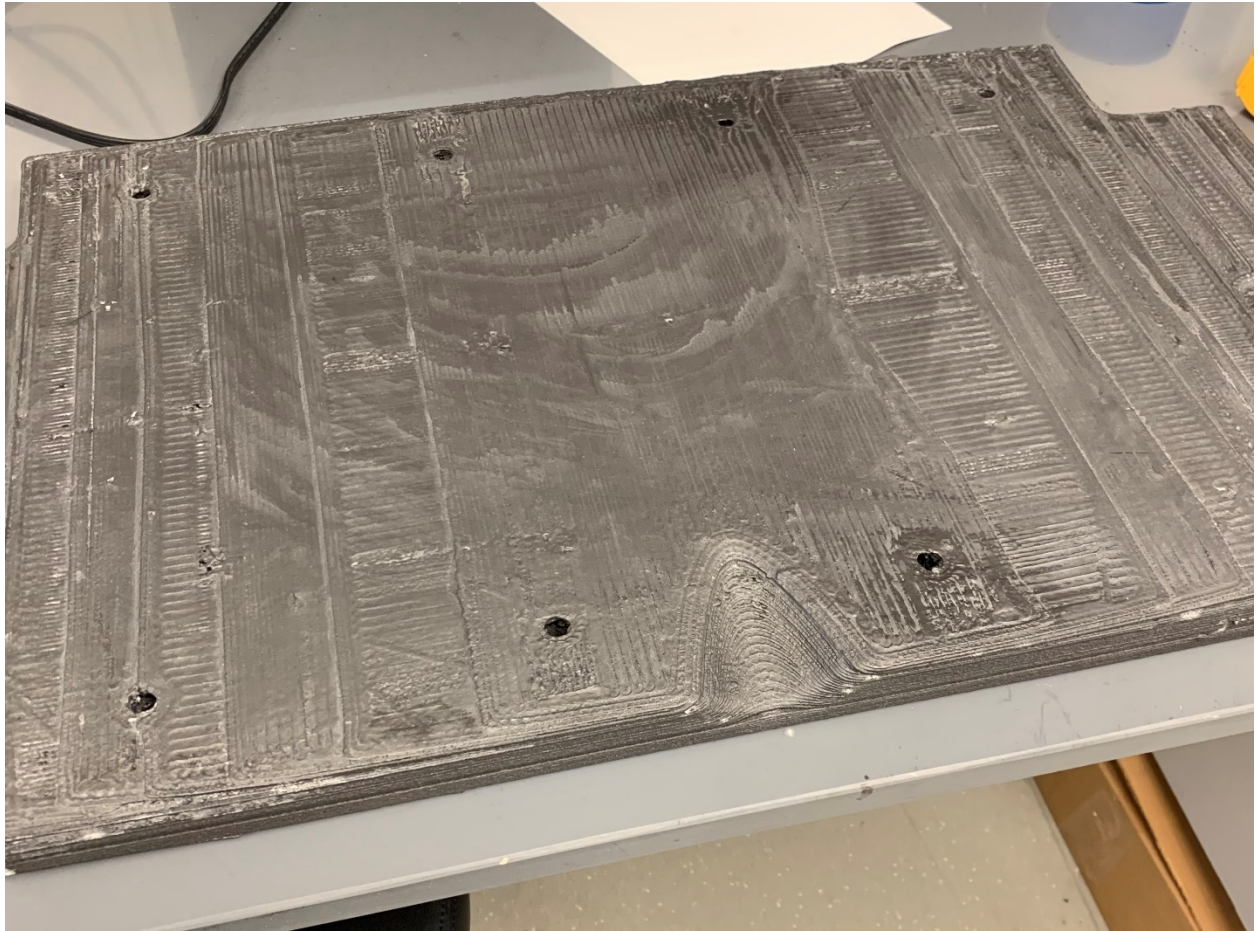


Figure 15. Mid-scale Printed High Thermal Conductivity Tool for Amana Refrigerator Door

While printable, the interfacial strength was limited and the tool split on removal from the print bed, and therefore was never tested at Amana before the project concluded. Ultimately, by refining the material performance, midscale systems could produce cost effective functional tools for this application.

1.3 IMPACTS

This project successfully demonstrated the capabilities of AM technologies in high volume applications like appliance manufacturing. Cost and lead-times can be reduced, by simplifying the tooling supply chain and improving the agility manufacturer. The development of new materials, processes, and techniques for heating and cooling tools have wide applicability across a range of materials. Likewise, the integration of appliance tooling manufacturers at Whirlpool and AM system

researchers at ORNL has resulted in additional technology demonstrations and projects that could revolutionize appliance manufacturing by reducing costs and improving the durability of stamping tools.

1.3.1 Subject Inventions

There are no subject inventions associated with this CRADA .

1.4 CONCLUSIONS

In this Phase 2 project, several new approaches were developed and tested for producing functional tools for refrigerator manufacturing. While many of the approaches met one or more of the criteria for success (i.e. durability, thermal conductivity, resolution, production rate, or cost), none of them have as of yet demonstrated the complete solution to this complex challenge.

With the rapid growth in AM capabilities over the course of this project, several new systems and materials were developed and tested, and future systems offer promise for low-cost AM at scales relevant to appliance manufacturers. Paths to commercial systems capable of addressing the needs of the appliance industry were investigated and ultimately, low-cost solutions for both systems and materials were determined.

2. WHIRLPOOL BACKGROUND

Whirlpool Corporation (NYSE: WHR) is the world's leading major home appliance company, with approximately \$21 billion in annual sales, 92,000 employees, and 65 manufacturing and technology research centers in 2018. The company markets Whirlpool, KitchenAid, Maytag, Consul, Brastemp, Amana, Bauknecht, JennAir, Indesit and other major brand names in nearly every country throughout the world. In 2018, Whirlpool and its associated brands sold 68 million products globally. 54% of those products were sold in North America. 22% of those products were sold in Europe, Middle East, and Africa. 17% of those products were sold in Latin America, and 7% of those products were sold in Asia.