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CRADA/ NFE-18-07325

CRADA Final Report: CRADA Number NFE-18-07325 with TCPoly, Inc.

Matt Smith

Date: August 31, 2020

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
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1. Abstract

TCPoly is commercializing high performance composite materials for the 3D printing industry and the company focus is manufacturing high thermal conductivity plastics for 3D printing of heat exchangers, electronic cooling devices, and mold tooling. Through the Innovation Crossroads Program, I was able to collaborate with ORNL researchers to expand the company's technology offering and revamp the company's business model and focus.

2. Statement of Objectives

The technical objectives can be broken down into three general categories: materials development, software development, and prototype production. Primary materials development tasks will be focused on producing a UL certified 3D printing filament with high thermal conductivity. Print optimization tasks will involve determining printing processes (toolpaths) and orientations that maximize throughput and thermal performance of parts manufactured with the high thermal conductivity filament. Prototype production tasks will involve working with potential customers to prototype new thermal management products in unison with efforts to validate and test the throughput and longevity of commercial FFF 3D printers.

3. Benefits to the Funding DOE Office's Mission

Our primary research accomplishments include developing Nylon and PPSU high thermal conductivity and high temperature stability 3D printing filaments (PPSU formulation is still in progress). These composite materials both have 20x higher thermal conductivity than their base material (10x higher than any other commercially available 3D printing plastic) and exhibit a 30% increase in temperature stability. Moreover, the PPSU formulation is an aerospace grade material with temperature stability over 250C and is inherently flame retardant with low smoke emission.

4. Technical Discussion of Work Performed by All Parties

TCPoly's unique high thermal conductivity 3D printing plastics provide value in three primary applications outlined below in Figure 1.

- Electronics thermal management for products such as lithium-ion batteries, LEDs, UAVs, CubeSats and power electronics (replacing metal heat sinks, cold plates, electronic cases)
  - Benefits: Lightweight, ultimate design freedom allows electronics to cool much faster, improving reliability and preventing premature failure. Materials can be electrically insulating and thermally conductive, flexible or bendable, and can provide electromagnetic interference shielding and electrostatic discharge properties.

- Additively manufactured heat exchangers with complex geometries
  - Benefits: allows for complex high-performance geometries that are also lightweight (about half the density of aluminum) and corrosion-resistant, resulting in high efficiency heat exchangers with improved reliability in the field.

• Additively manufactured tooling with thermal properties comparable to conventionally manufactured metal molds

o Benefits: has the potential to extend the lifetime of additively manufactured tools, reduces lead times and costs associated with manufacturing tools conventionally (metal machining), helps with part cooling and creates an even temperature distribution throughout the tool and molded part, improving part quality.

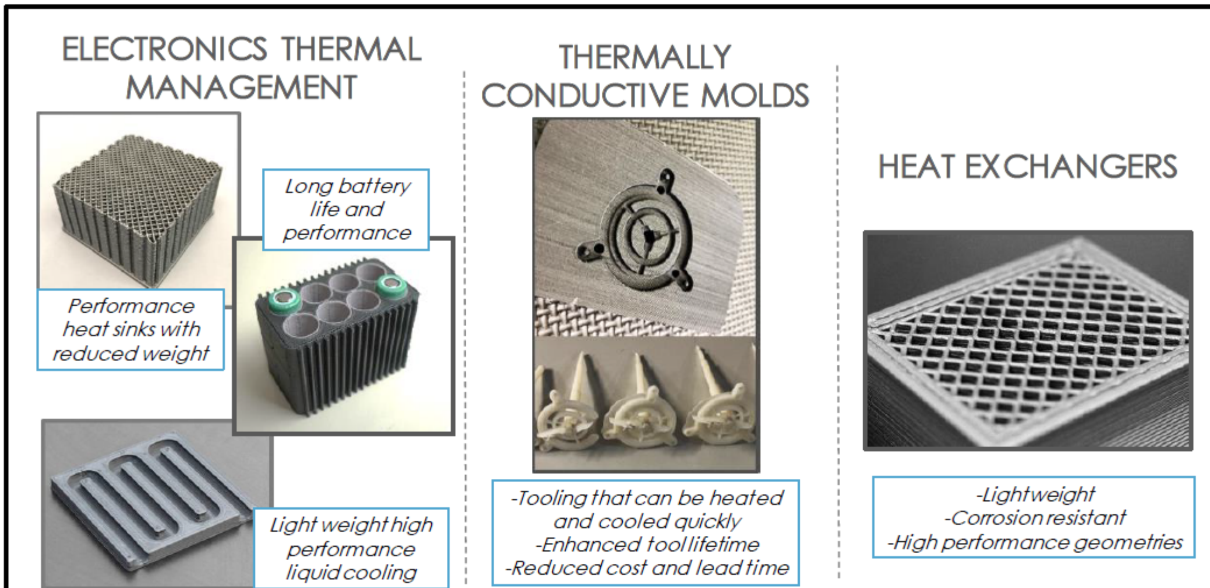


Figure 1. TCPoly materials are being adopted in several markets including electronics thermal management, 3D printed mold tools, and 3D printed heat exchangers. The primary use of our material in each category is metal replacement and the potential value props are highlighted.

At the beginning of this appoint, TCPoly materials were only able to operate at temperatures up to 100C. However, many applications (especially for mold tooling) require materials with temperature stability above 150C. Therefore, one of the primary research initiatives was to develop filaments with increased temperature stability. This was particularly challenging because high temperature materials tend to exhibit brittleness when loaded with thermally conductive fillers. Through small scale materials formulation efforts utilizing DOE resources and expertise at ORNL, we were able to successfully formulate a nylon-based filament with thermal conductivity of 4 W/m-K (20x higher than a standard nylon). This material has been adopted as a product line and is currently being commercialized. In addition, a PPSU based aerospace grade material has been successfully printed and is expected to be finalized in the next few months. Below is a table comparing TCPoly high temperature materials to Stratasys Digital ABS material.

20x HIGHER THERMAL CONDUCTIVITY THAN STANDARD PLASTICS	TCPoly Rigid (Nylon)	TCPoly Aero (PPSU)	Stratasys Digital ABS
Printing Method	FDM	FDM	Polyjet
Thermal Conductivity (W/m-K)	4	4	0.2
Heat Deflection Temperature, 0.45 MPa (°C)	190	250	95
Hardness (Shore)	70D	90D	87D
Tensile Modulus (GPa)	4	5	5
Tensile Strength (MPa)	50	60	75

One of the most common products used to cool electronics of metal heat sinks and we were able to demonstrate that TCPoly plastics could be used to 3D print plastic heat sinks with performance equivalent to metals, but at half the weight. More specifically, TCPoly's high thermal conductivity 3D printing filaments were used to determine the thermal conductivity of 3D printed heat sink as a function of print orientation. Filament in-plane, through-plane, and cross-plane thermal conductivity was measured, and these values were used to predict a 3D printed heat sink's thermal performance as a function of print orientation using finite element methods. Finally, the thermal performance of the 3D printed heat sinks was evaluated to determine heat sink effectiveness and model robustness. The results demonstrate an in-plane thermal conductivity ranging from 3.6 to 11.9 W/m-K and a 3-6x anisotropy ratio between in-plane and through-plane thermal conductivity. The cross-plane thermal conductivity is typically 2x the through-plane thermal conductivity. The finite element modeling agreed well with experimental measurements on 3D printed heat sinks and a 3D printed composite heat sink with in-plane thermal conductivity oriented parallel to the heat sink base (aligned parallel to the heat transfer direction) demonstrated performance comparable to that of an Aluminum heat sink with similar geometry. These findings were published in collaboration with ORNL researchers and was presented at ITERM (https://ieeexplore.ieee.org/abstract/document/8757285). The primary results are highlighted below in Figure's 2, 3 and 4.

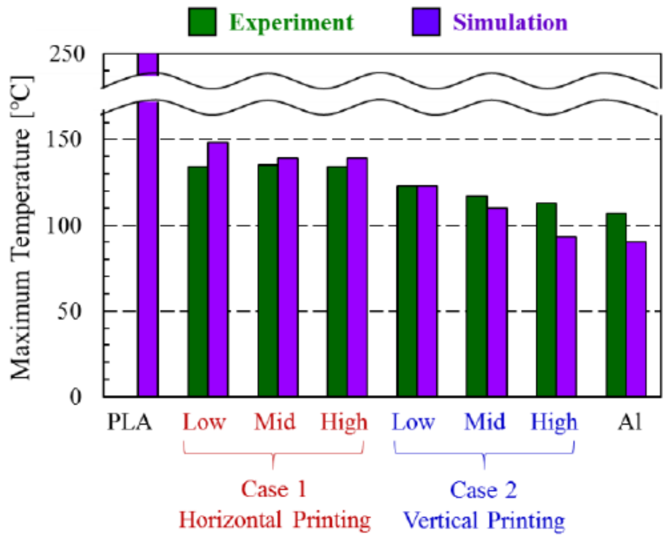


Figure 2. Heat sink performance (indicated by maximum heater temperature) as a function of heat sink print orientation and material thermal conductivity.

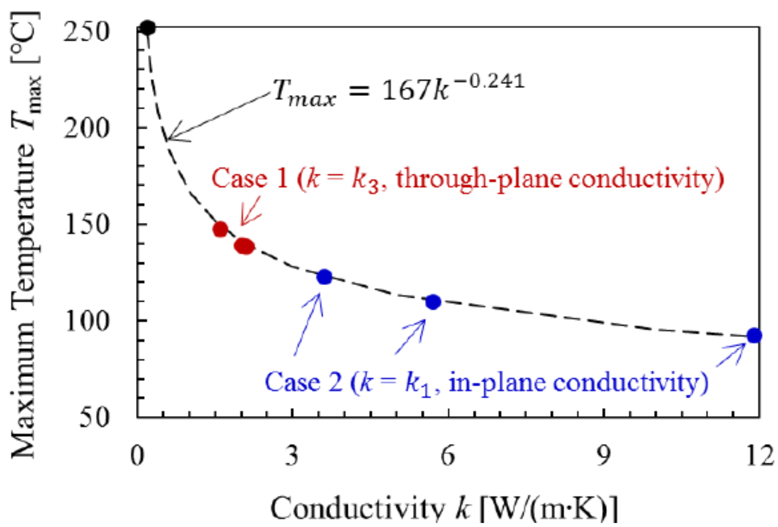
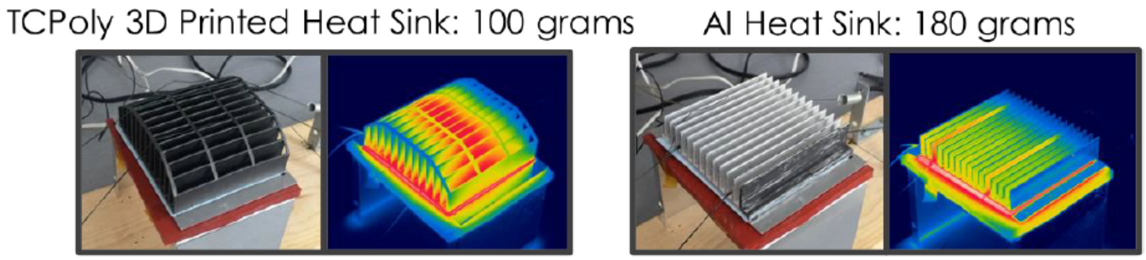


Figure 3. Maximum heater temperature (at constant power) as a function of conductivity of various polymers. The conductivity k is for the direction perpendicular to the heat sink base surface.



	TCPoly Heat Sink	Extruded Aluminum Heat Sink
Fin Height	15 – 33 mm	20 mm
Number of Fins	13	13
Base Dimensions	100x100 mm	100x100 mm
Resistance	2.2 °C/W	2.1 °C/W
Weight	100 grams	180 grams
Thermal Conductivity	8 W/m-K	160 W/m-K

Figure 4. Comparison of a TCPoly 3D printed heat sink's thermal performance with the performance of an aluminum heat sink. For nearly equal thermal resistance, the TCPoly heat sink is ~40% less weight.

We were also able to 3D print liquid cooling devices such as liquid cold plates to demonstrate TCPoly's material performance in a liquid cooling application. Liquid Cold Plates are widely becoming a critical cooling solution for electronic devices. Cold Plates pass a coolant (usually glycol or water) through a conductive plate. When the plate is a placed on a hot device, the heat is spread into the plate and removed via convection in the coolant. Traditionally, these devices have been made of metals, primarily aluminum. However, using TCPoly's conductive polymers it is possible to create 3D-printed plastic cold plates. These devices are lightweight, low cost, fully customizable, and have short lead times. However, to compete in the market against traditional cold plates, it was necessary to benchmark the performance of TCPoly plastic cold plates. Cold Plate performance is usually evaluated using 2 metrics – pressure drop and thermal resistance.

Pressure Drop Testing and Results

Pressure drop is the amount of pressure lost as the coolant flows through the system. Low pressure drop is desirable, as it requires less energy to pump coolant through such a system. Pressure drop is acquired by measuring the pressure differential between the entry and exit of the system. Pressure drop is a function of flow rate. Selected results of the pressure drop testing are given in the following section.

Thermal Resistance Testing and Results

Thermal resistance is a measure of how easily heat can flow through a system. Typical metal cold plates have very low thermal resistance, as metal is a good conductor of heat. While plastics are typically insulating and have a relatively high thermal resistance, TCPoly plastics have high thermal conductivity up to 50x higher than these traditional plastics. Thus, it is possible to manufacture plastic cold plates that are similar in performance to traditional metal cold plates. Thermal resistance was measured by collecting the surface temperature of the cold plate and the temperature of the cooling fluid. By using a heater of a known wattage, it was possible to determine the thermal resistance of the cold plates. The results of the experimentation are shown below in Figure 5.

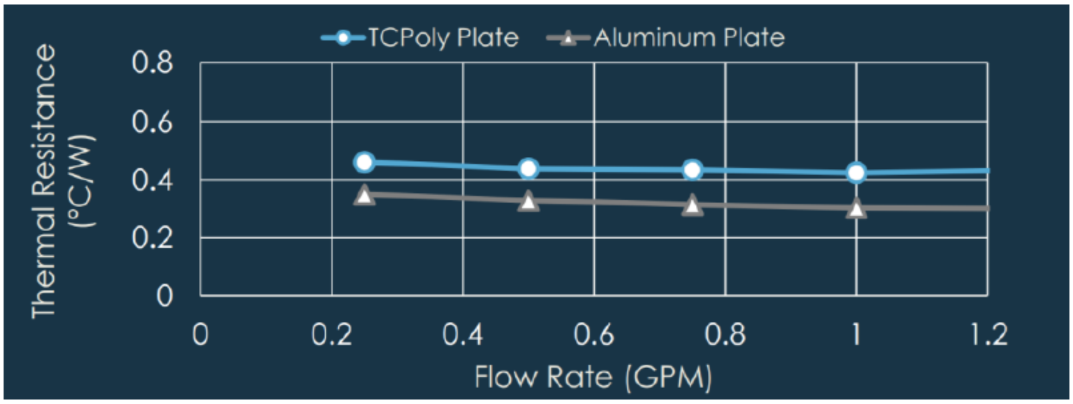
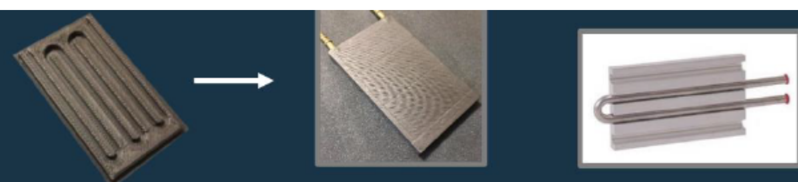


Figure 5. Thermal resistance vs flow rate for a 3D printed liquid cold plat and a commercially available aluminum cold plate.

As shown, the TCPoly cold plate performs similarly to the traditional aluminum cold plate. When normalized by weight, we see that TCPoly cold plates drastically outperform traditional cold plates. A summary of the cold plate performance is below in Figure 6.



	TCPoly All Plastic	**Lytron CP10G03**
Active area	150x90 mm²	150x90 mm²
Cooling Fluid	Water	Water
Flowrate	1.0 gpm	1.0 gpm
Weight	150 g	500 g
Weight Normalized Resistance*	67.5 g-°C/W	170 g-°C/W
Resistance**	0.4 °C/W	0.34 °C/W

**Calculated by multiplying the thermal resistance by the weight .*
***Measured value using in-house test at 1 GPM flow rate . The Aluminum cold plate manufacturer value is 0.07 ˚C/W.*

Figure 6. Thermal performance and general properties of TCPoly 3D printed cold plates compared to a commercial aluminum product.

During the past year we have visited several conferences in the thermal management space including Semi-Therm, iTherm, Rapid+TCT, the Light Show, and Defense TechConnect, and have been working with many customers in these industries. We have learned that despite some early customer adoption, these markets will be difficult to penetrate at high volumes in the short term due to long development cycles, the need for stringent material certifications, and an unfamiliarity (and general distrust) of 3D printing technologies. Hence, we have pivoted to focus on the mold tooling market and our target beachhead market of vented tooling for lost foam casting (Figure 7).

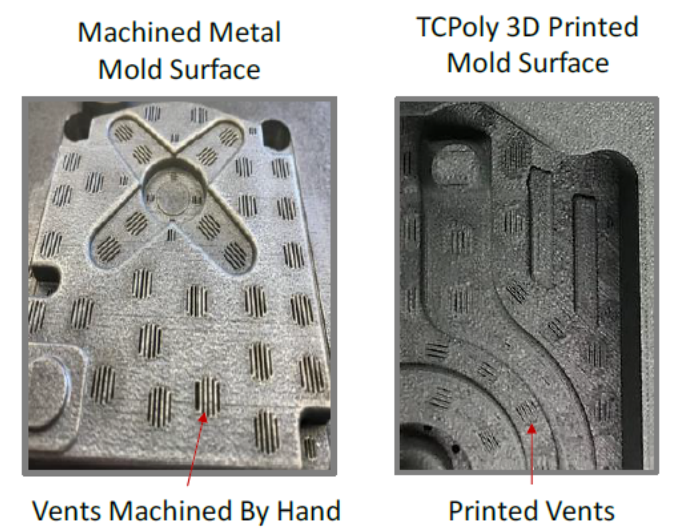


Figure 7. Comparison of metal machined and plastic 3D printed LFC mold surfaces.

In the lost foam casting (LFC) process, polystyrene or other polymer foam parts are molded using pressure and steam (forming parts like a Styrofoam cup). The molded foam parts are then encased in sand and molten metal is poured onto to Styrofoam "target" to burn out the foam, and metal parts is formed. To make the foam parts, a metal mold with micron sized vents is filled with foam beads and then steam enters the mold through the vents to expand and bond the beads into a fused foam part. These molds are typically machined from aluminum or steel and then machined by hand to smooth the surfaces and insert the vents. Moreover, we have learned that for a moderately sized mold (about 15x15x6 cm in volume, or approximately 1.5 kg of TCPoly material) the lead time is 20 days, the cost is around $8,000, and the design of both the venting channels and molded part is limited by what is possible through machining. Whereas a TCPoly materials enable a working tool for less than $500, a 2-day lead time, and increased design freedom.

Figure 8. Recent TCPoly engagements in the mold tooling market.

5. Subject Inventions (As defined in the CRADA)

None.

6. Commercialization Possibilities

These materials were utilized on several projects in collaboration with ORNL researchers including a mold tooling project sponsored by Whirlpool (working with Dr. Brian Post), a heat exchanger project sponsored by Sulzer (working with Dr. Lonnie Love), and another heat exchanger project sponsored by the DOE (working with Dr. Vlastimil Kunc, Dr. Ahmed Hassan and Dr. Kahif Nawaz). In addition, TCPoly collaborated with ORNL researchers to test materials properties as a function of printing conditions and these findings were published and presented at various academic and industry conferences.

7. Conclusions

The successful demonstration of these products in application enabled TCPoly to expand our product offering and to grow our market reach. During the appointment, we have sold materials into over 15 countries and now have distributors in the USA, Europe, and Australia. Our filaments are listed on McMaster Carr and we are working with several customers on development projects to prove our materials at production scale. Based on continued customer discovery, we have pivoted into our new market focus of 3D printed mold tooling and we are using our high performance material to 3D print plastic molds to replace metal molds with enhanced designed freedom, lost cost, short lead times, and at a fraction the amount of embodied energy. Through outside investment and an NSF SBIR Award, TCPoly is planning to move forward to continue to grow our company and enable technology innovation through advanced materials and manufacturing methods.

TCPoly is actively working to raise additional funds through government grants and seed investment. We have begun a collaboration with NREL to incorporate heat storage in our materials (using phase change composites) and have applied for several grants including a DOE STTR. We have identified the mold tooling market as our beachhead and are working with several commercial partners to drive adoption. By replacing metal molds with 3D printed plastic molds, TCPoly materials enable rapid innovation through a merger of additive manufacturing with traditional manufacturing processes. I plan to continue my role as CEO of TCPoly.