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Additively Manufactured Heater for a Polymer Slot Die Coater

by Scott Bernetich and Eric D. Wetzel

NOTICES

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14. ABSTRACT
An aluminum alloy heater body is designed and fabricated via metals additive manufacturing (AM) to enable liquid heating of a polymer slot die used in the production of polymer films. The design incorporates internal flow channels for heated fluid circulation, allowing for precise temperature control and minimal temperature fluctuations. The heater bodies are fabricated via Direct Metal Laser Sintering (DMLS) with AlSi10Mg powder. The use of AM allows for the creation of complex internal flow channels, which would be difficult to fabricate with conventional machining. Post-machining operations are used to refine critical surfaces and ensure dimensional accuracy for integration with the existing device. Thermal measurements demonstrate the excellent performance of the heater body and confirm the benefits of metals AM for creating custom heat exchangers with complex internal geometries.

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1. Introduction

U.S. Army Combat Capabilities Development Command Army Research Laboratory is collaborating with the Rochester Institute of Technology (RIT) to demonstrate slot die coating of polymer films. In slot die coating, a thin film of liquid pre-polymer is deposited onto a moving web.[1] The pre-polymer can comprise reactive monomers that polymerize after deposition, or a polymer solution that converts to a solid film after solvent evaporation. The pre-polymer is fed from a flow-controlled pump into the slot die, with the flow rate, die shape, slot dimensions, and slot-to-web distance carefully designed and controlled to achieve a uniform and high-quality coating. Slot die coating is practiced industrially and can be scaled to wide webs and very high linear web velocities.

In standard slot die coating, the pre-polymer solution is coated at room temperature. However, for some materials, it is desirable to deposit the pre-polymer at elevated temperatures. For these processes, a means of heating the slot die is necessary.

In this report, a slot die heater is designed and fabricated via additive manufacturing (AM). Heating is provided via circulation of heated fluid through internal flow channels. The heater is designed to retrofit onto an existing slot die. AM was chosen because of its ability to directly build tortuous internal flow channels, which would be difficult to fabricate via conventional machining. Liquid heating was chosen to enable precise heating control, while reducing the likelihood of temperature swings due to process or environmental changes.

2. Design

The goal of the slot die heater was to fit easily over the die itself, making good contact with the surface for thermal conductivity, while not interfering with the deposition of polymer solution during coating. Figure 1 shows the slot die coating machine; Figure 2 shows details of the slot die. Other design interests included maximizing channel coverage, reducing thermal resistance, and implementing features that enable the heater to self-align on the slot die.

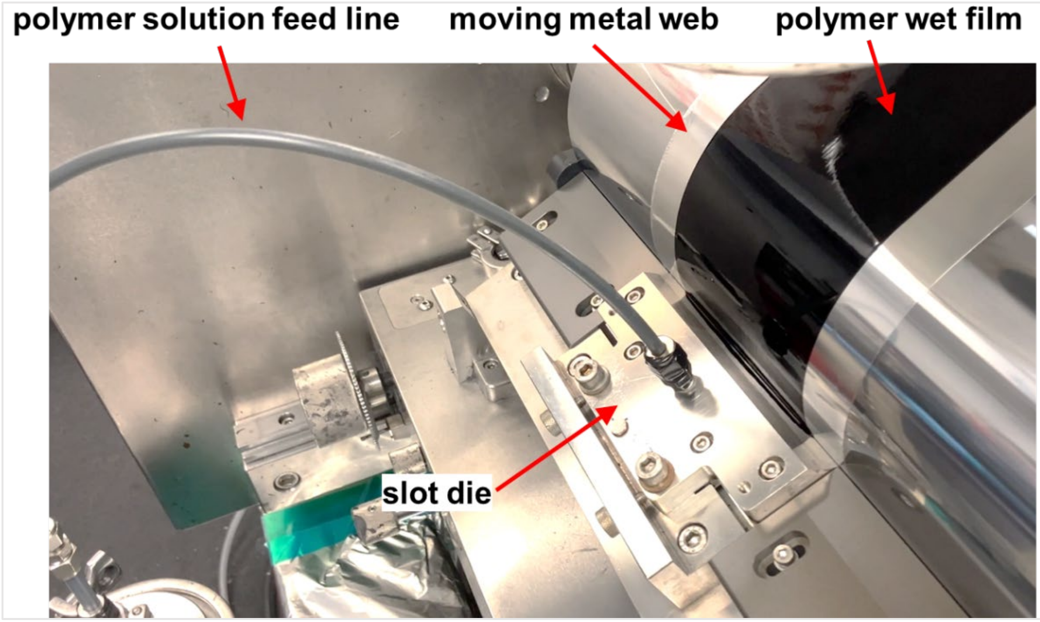

Figure 1. **Photograph of the slot die in the coating machine.**

Figure 2. Model (top) and photograph (bottom) of the slot die.

Figure 3 shows the conceptual slot die heater design. It incorporates an internal flow channel designed to maximize heat transfer and ensure an even temperature distribution across the slot die surface. Two overhangs at the rear of the heater enable repeatable alignment and assembly between the heater and the die. Two cylindrical recesses were included to provide clearance relative to mounting hardware on the slot die. Female holes at inlet and outlet ports are sized for post-print threading to receive compression fittings.

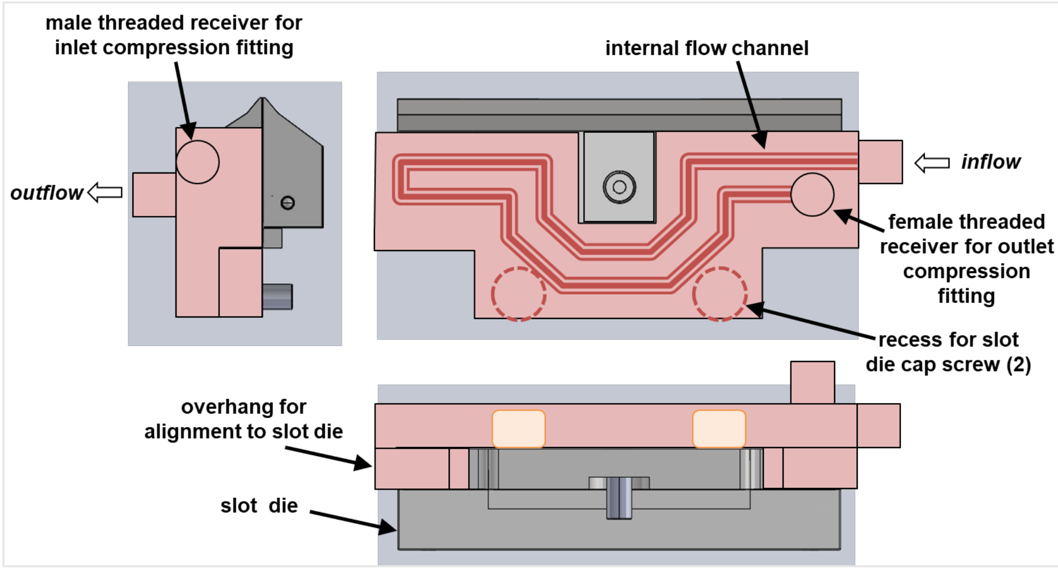

Figure 3. Conceptual schematic of the slot die heater.

Figure 4 shows a 3D-printed, polymer prototype that was printed and test fit as part of the design iteration process. Two design changes were made through this physical prototyping process. First, the original conceptual design called for recesses in the heater body to accommodate the existing cap screws that mount the slot die to the coating machine. However, after test fitting, it was decided instead to lengthen the mounting cap screws and design the heater body recesses so that the cap screws could clamp the heater body and die together to the coating machine. This approach provides better alignment and thermal contact between the heater body and slot die. Second, the side overhangs were removed, because the combination of rear overhangs and through-bolting the heater body provides sufficient alignment.

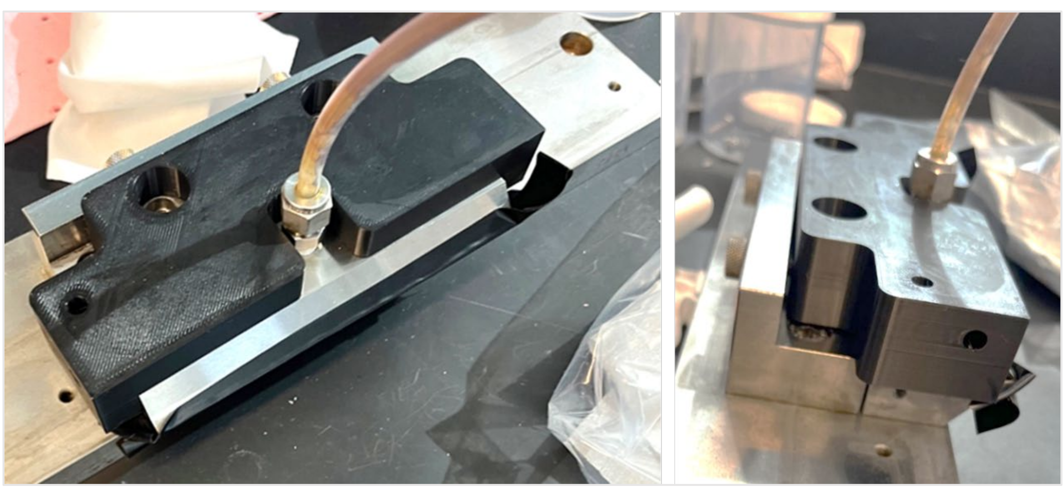

Figure 4. Early-stage, 3D-printed polymer prototype of the slot die heater.

When selecting the channel geometry and size, circular profiles were chosen due to their manufacturability in AM and uniform surface heat transfer during internal flow circulation. Multiple diameters of circular channels were printed horizontally to test the effects of distortion and dross defects (i.e., undesirable metal buildup and artifacts on overhang features).[2,3] The 5-mm-diameter channel was selected based on balancing a number of factors including printed surface quality, flow capacity, resultant wall thickness, and ability to pack densely within the geometry. Figure 5 is a cross section of the 3D computer-aided design (CAD) model showing the internal channels of the heater design produced and the solid supports used to secure the model to the print bed while manufacturing. The vertical sections of conformal channels were adjusted to reduce distortion and the regions around the polymer inlet were adjusted to fit geometric constraints. Solid supports help combat the curling forces of residual stress making them required while producing large models such as this with Direct Metal Laser Sintering (DMLS). To allow for post machining to reach dimensional accuracy, the part was overbuilt (i.e., increased slightly in size) in critical dimensions and on mating surfaces. The fully rendered heater design, integrated with the slot die, is shown in Figure 6.

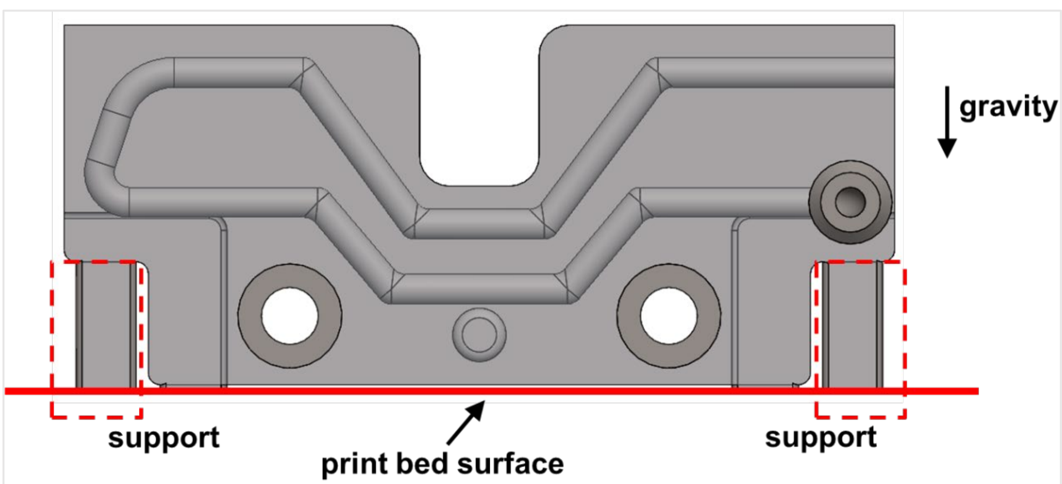

Figure 5. Transparent view section of heater model with serpentine channel and solid supports.

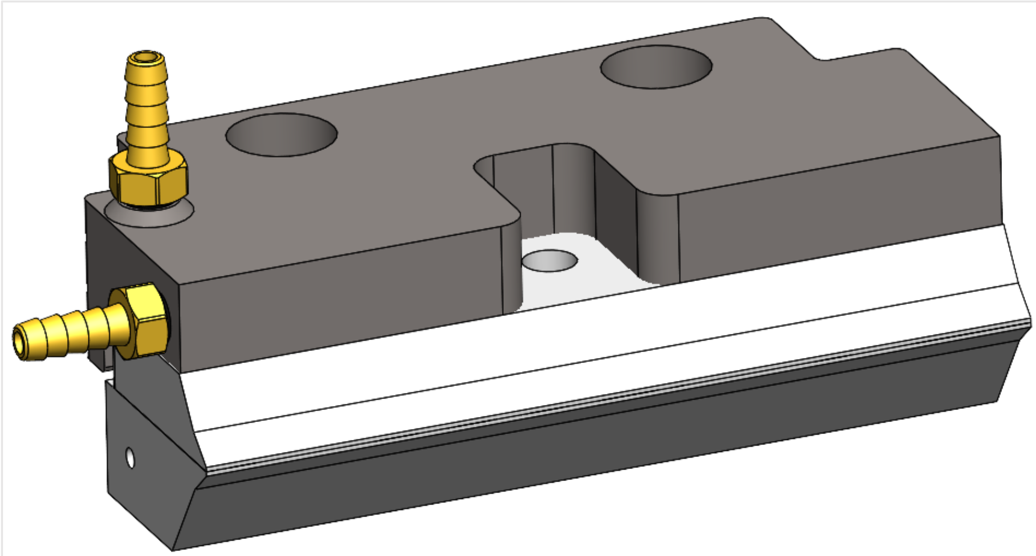

Figure 6. **3D model of the finalized heater design with fittings, mounted to the slot die.**

3. Fabrication

The fabrication of the slot die heater involved two main stages: AM to create the overall geometry with complex internal channels, and post machining to refine critical surfaces and ensure proper fit.

Powder Bed Fusion using an EOS (Novi, Michigan) M290 DMLS system was selected for its ability to produce high-resolution parts with complex geometries and internal features. AlSi10Mg powder was chosen for its additive manufacturability in addition to its high thermal conductivity and low weight. As an AM powder feedstock it flows well, leading to a consistent melt pool and low porosity while the added silicon content improves fluidity and reduces susceptibility to cracking. The 3D model of the heater, which was designed in SolidWorks (Dassault Group; Vélizy, France) CAD software, is converted into an STL format that can be processed by the DMLS slicing software. Solid support structures were modeled into the part itself while the breakaway supports were added via the slicer. Both styles anchor the part to the build plate during printing to prevent deformation caused by residual stress and allow for a maximum overhang angle. The build platform was prepared by roughing the surface with an orbital sander, and the AlSi10Mg powder was loaded into the machine. The DMLS system operates by depositing thin layers of metal powder across the build plate, which are then selectively melted using a high-powered fiber laser system to form the geometry layer-by-layer. Figure 7 shows the completed build plate and the combination of solid and breakaway supports used to support the part during printing. After the build is complete, excess powder is removed and sieved for reuse. The build plate, with the part still welded to it, goes to the furnace for a stress relief cycle of 90 min at 270 °C (per manufacturer specifications). This step is performed to help prevent curling and cracking while removing the part from the bed.

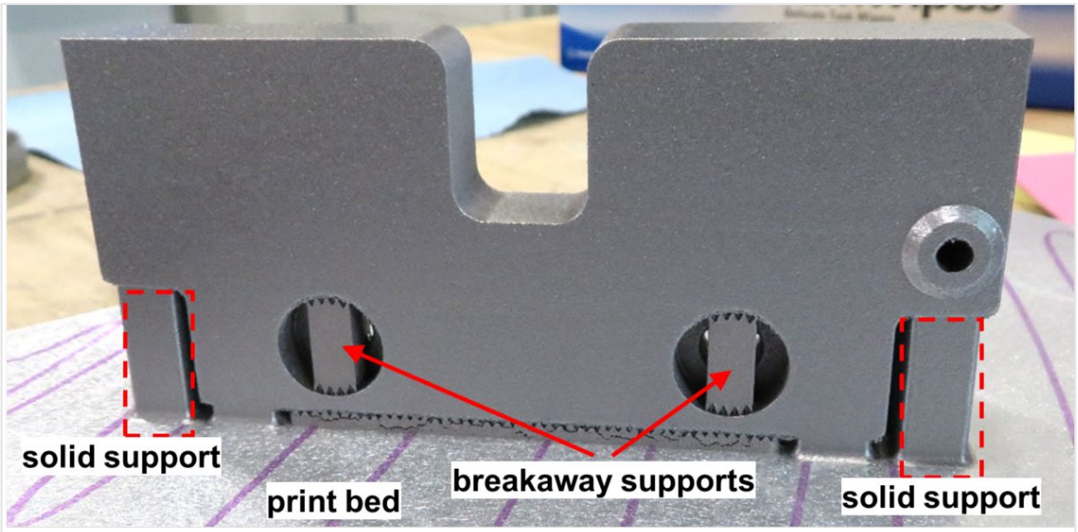

Figure 7. Photograph of slot die heater still welded to build plate, showing both solid and breakaway supports.

While AM offers excellent design freedom, certain critical surfaces required post machining for optimal performance and integration. The first step is the removal of support material: solid supports are cut through with a bandsaw and the breakaway supports are removed with chisels and pliers. Figure 8 shows the freed part. The as-printed surfaces from DMLS systems can be rough; thus, computer numerical controlled machining systems were used to smooth the surfaces that interface with the existing slot die, ensuring proper contact and heat transfer. This post machining included the overbuilt areas such as the bottom surface of the heater as well as any alignment features. Critical features such as the fluid inlet and outlet ports were machined to ensure accurate dimensions and surface finish for leak-free connections. Threads were tapped in these ports for fittings, which allow connection of the heated liquid lines. The overall dimensions of the heater were precisely machined to tight tolerances to ensure accurate and repeatable positioning on the slot die. Finally, after machining, the heater was thoroughly cleaned to remove any debris from machining and trapped powder.

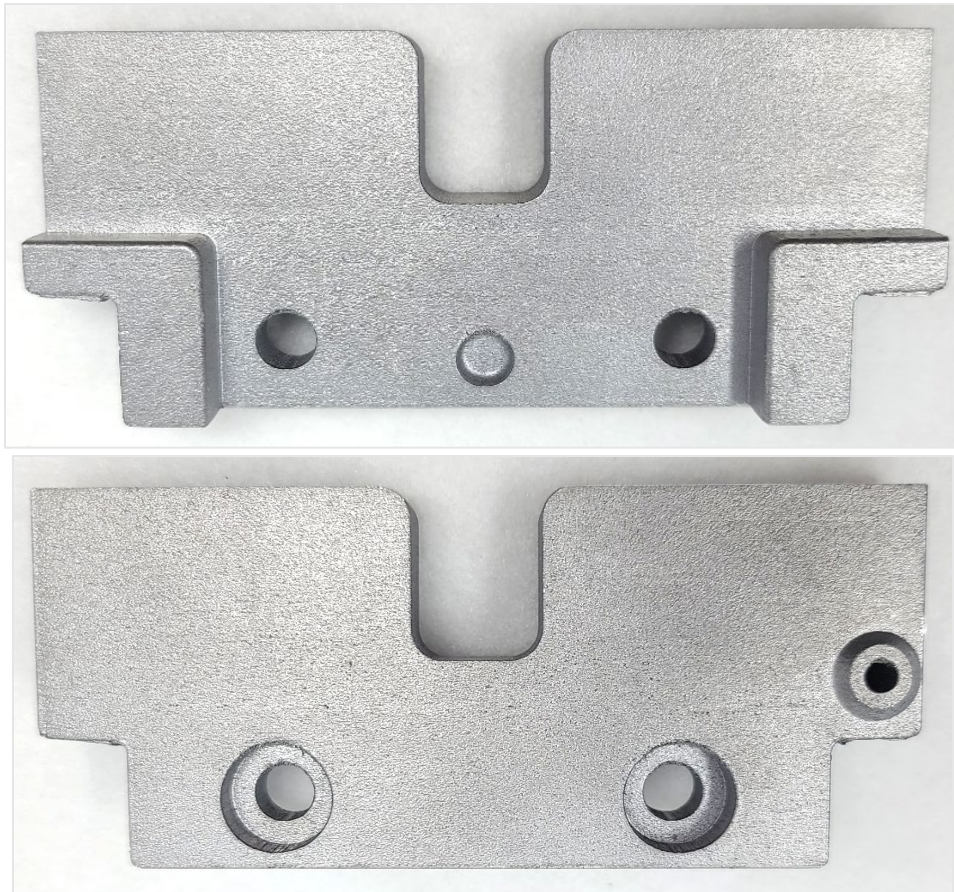

Figure 8. Photographs of heater with as-printed surface finish (top) and supports removed (bottom).

This combined approach of AM and post machining allowed for the creation of a complex, high-performance heater with the required precision and functionality for integration into the slot die coating system (Figure 9).

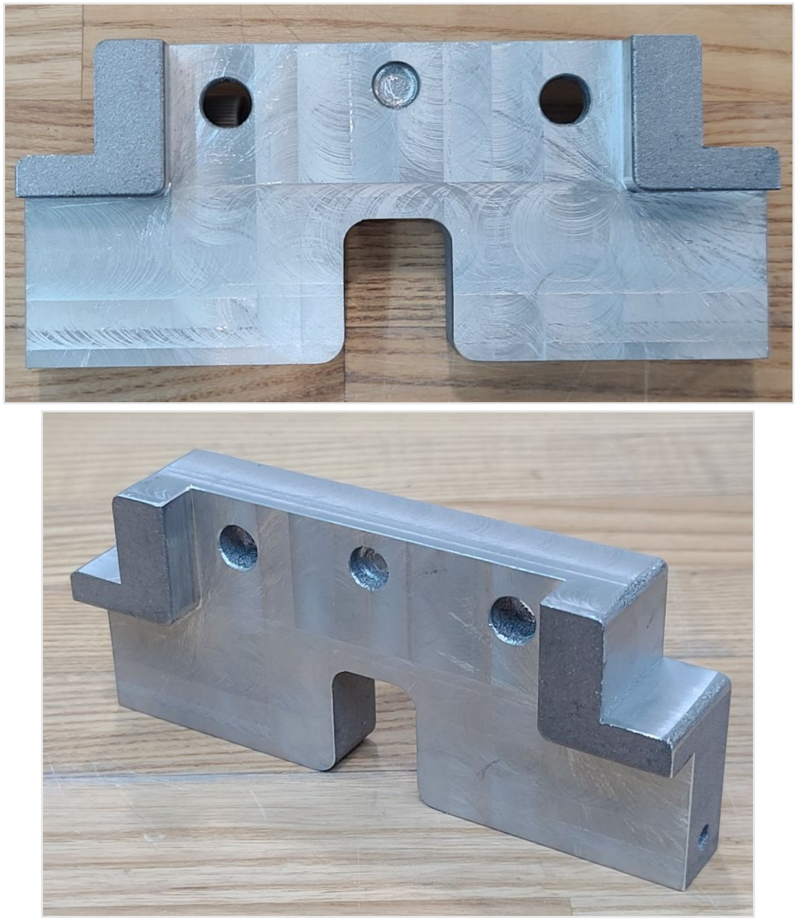

Figure 9. Photographs of the slot die heater after post-machining process.

4. Result

Figure 10 shows the fabricated and finished slot die heater. Final machined dimensions at critical surfaces were within 0.2 mm of design dimensions. Figure 11 shows a heating trial with the slot die heater, in which ethylene glycol at 60 °C was circulated through the slot die heater while measuring the temperature with a Teledyne FLIR (Wilsonville, Oregon) AX5 IR camera. The thermal images were analyzed using FLIR ResearchIR v4.40 software with an assumed surface emissivity of 1.0. The bright area of the image is where Kapton tape was added to the surface to provide emissivity for IR measurements, as the bare aluminum surface does not have sufficient emissivity for IR measurements. The temperature uniformity throughout the slot die heater is excellent.

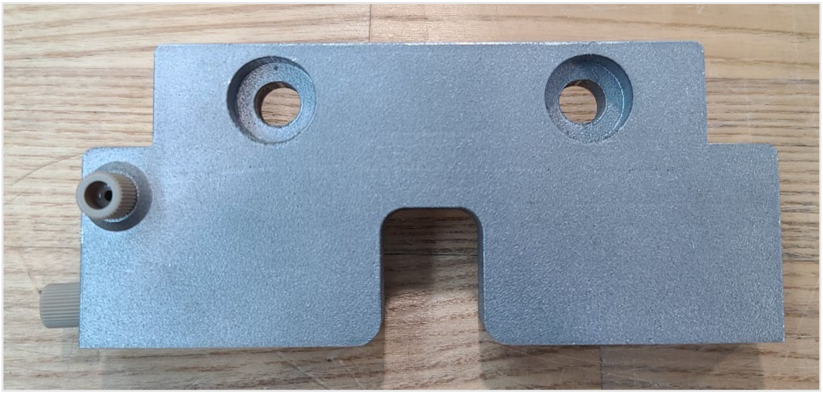

Figure 10. Completed slot die heater from above with fittings.

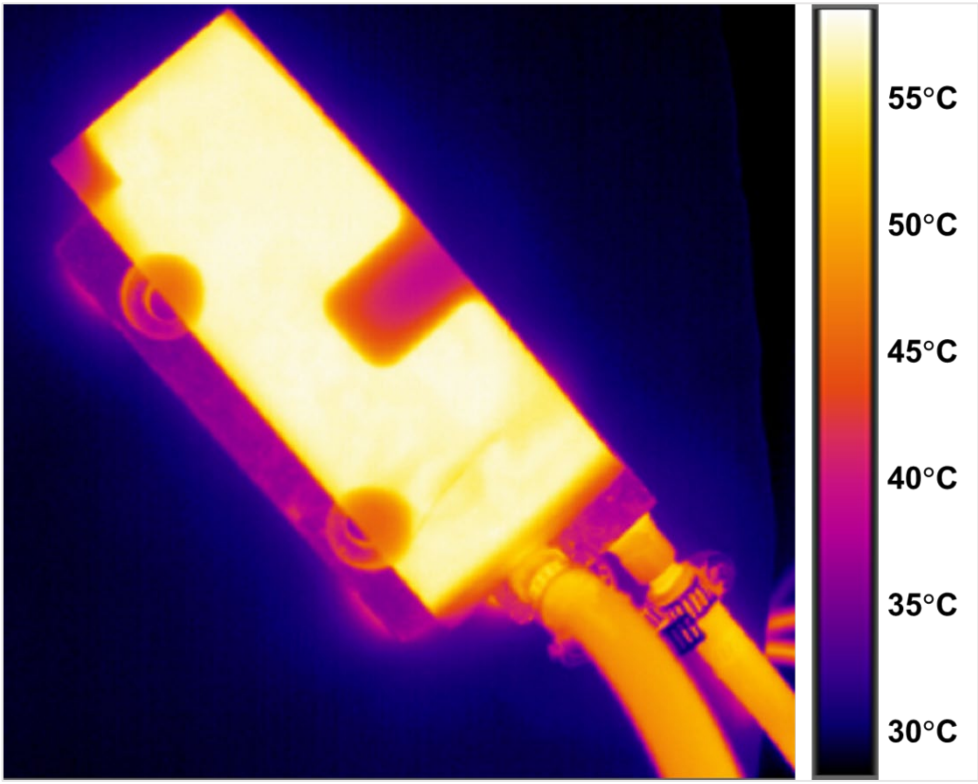

Figure 11. Thermal images of testing during liquid heating. Kapton tape was placed across the top surface to improve emissivity during imaging.

Figure 12 shows the slot die heater mounted on the slot die coating machine, a custom pilot-scale film machine made by Delta ModTech (Ramsey, Minnesota). The slot die heater fit is excellent and should meet heating requirements. Heated polymer deposition runs are expected to be undertaken during upcoming investigations.

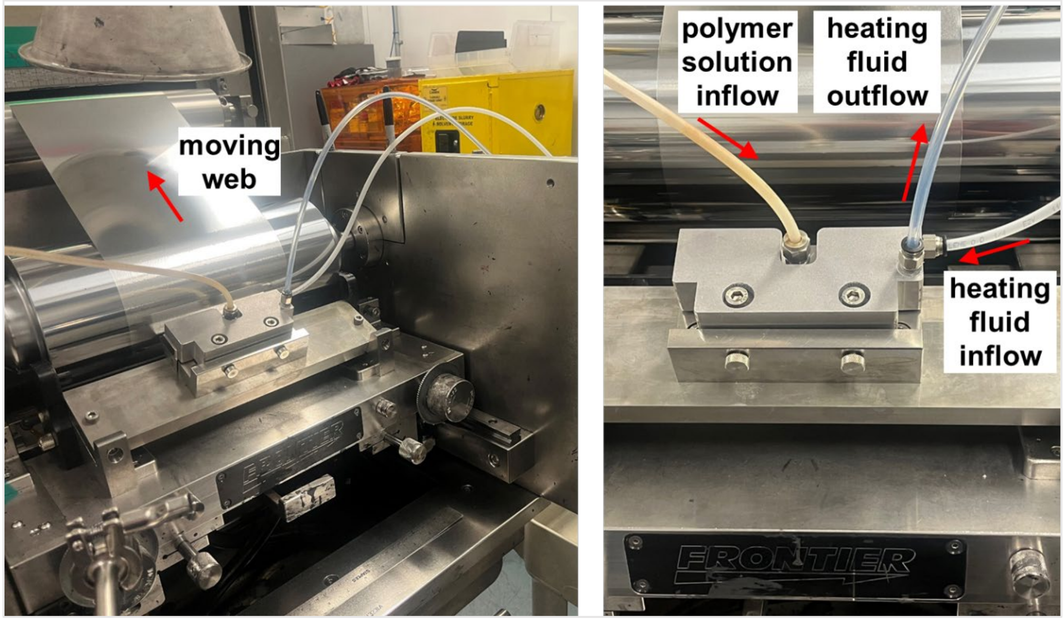

Figure 12. Slot die heater mounted on polymer slot die roll-to-roll coating machine.

5. Conclusions

This report demonstrates how CAD design and AM can be used to create robust and efficient liquid-heated metal bodies for material process lines. The use of liquid heating is particularly enabled by AM because of the challenges associated with using conventional machining to create tortuous internal flow channels in metal tooling. A further advantage of additively manufactured parts is that the part files are stored digitally; therefore, new heater bodies can be fabricated in the future by simply executing one or more additional prints. Heating trials with this slot die heater will be undertaken to validate the design and confirm heating performance.

6. References

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3. Han Q et al. Manufacturability of AlSi10Mg overhang structures fabricated by laser powder bed fusion. Mater Des. 2018;160:1080–1095.

List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
AM	additive manufacturing
ARL	Army Research Laboratory
CAD	computer-aided design
DEVCOM	U.S. Army Combat Capabilities Development Command
DMLS	Direct Metal Laser Sintering
IR	infrared
RIT	Rochester Institute of Technology

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