Design, Material, and Manufacturing of a Heat Exchanger with Fused Filament Fabrication

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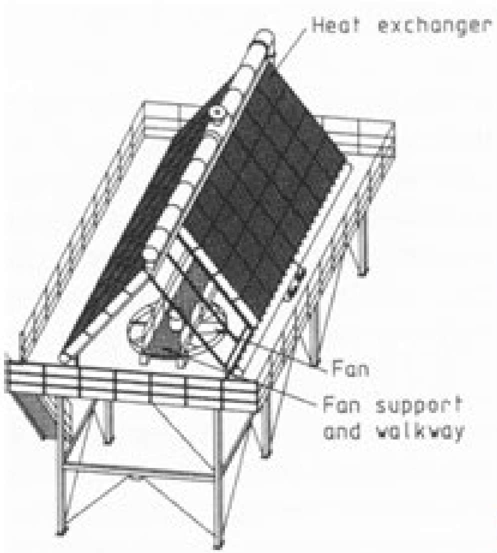
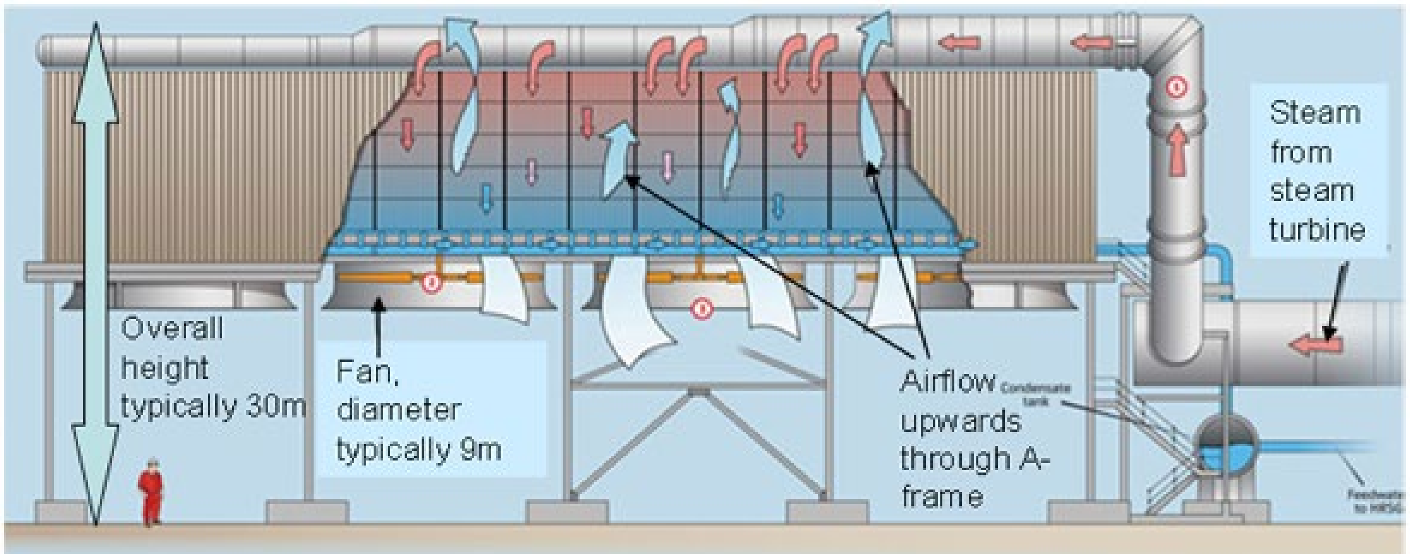
Air-Cooled Heat Exchangers

- The Department of Energy financed projects in advanced heat exchangers, ideally for combustion power plants
- Later on, our industrial partner decided to target commercial HVAC systems





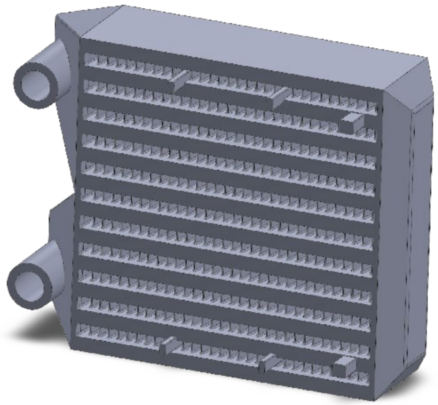
https://www.eac.com.cy/EN/EAC/ResearchandDevelopment/Pages/MACCSol.aspx

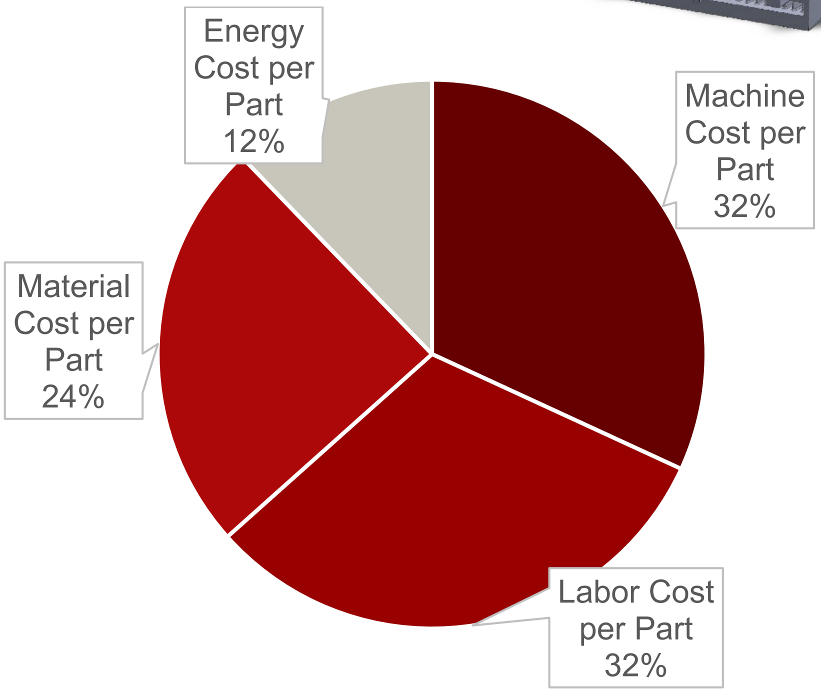
FFF Production of Air-Cooled Heat Exchangers

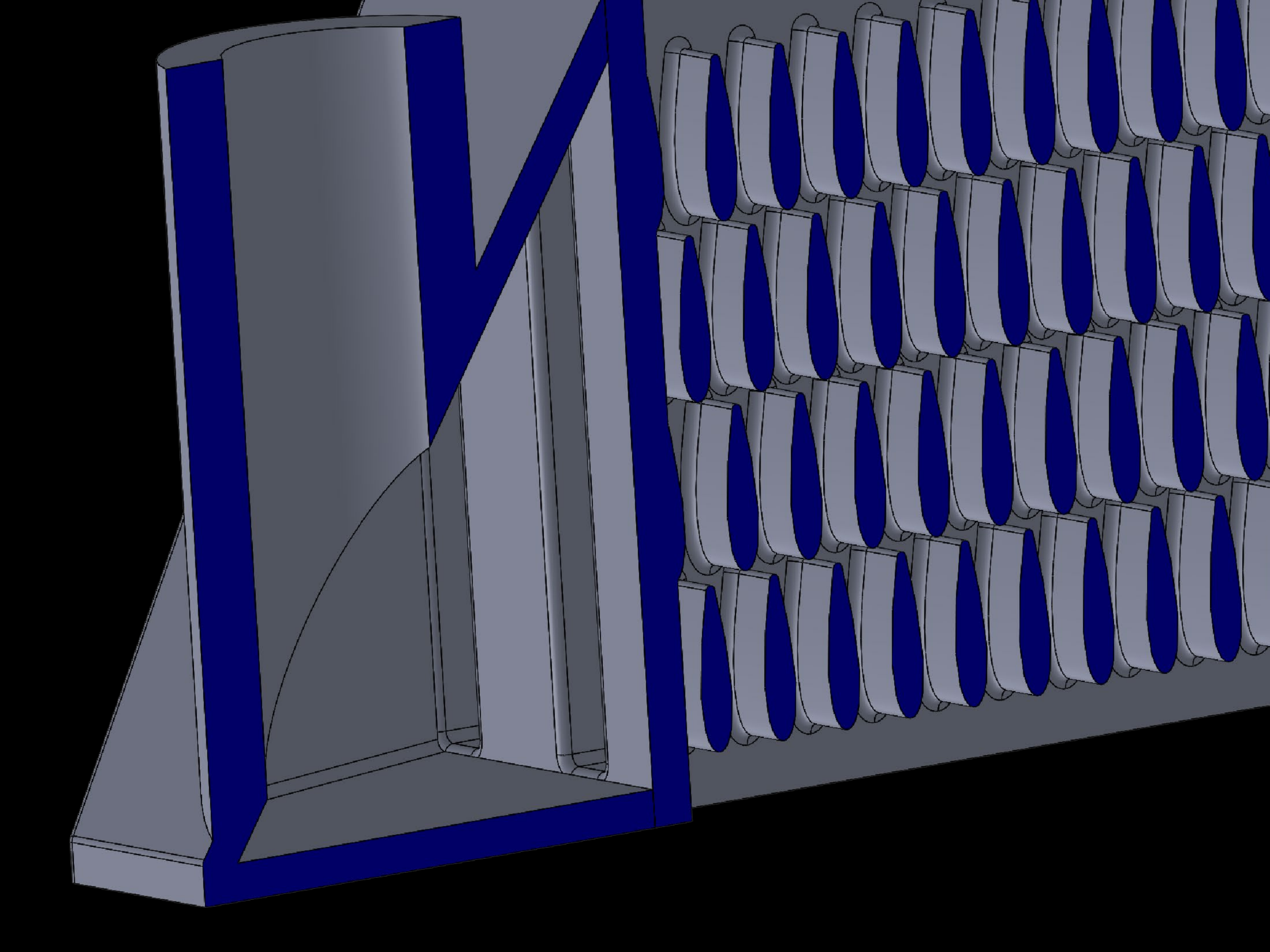
Why use Fused Filament Fabrication?

- Geometric freedom
- Low machine and material cost
- Easily work with composite materials
- Easily use multiple materials
- Surface finish and aesthetics

  are not a principal concern

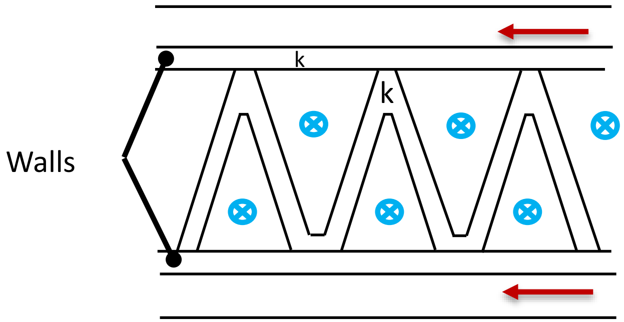




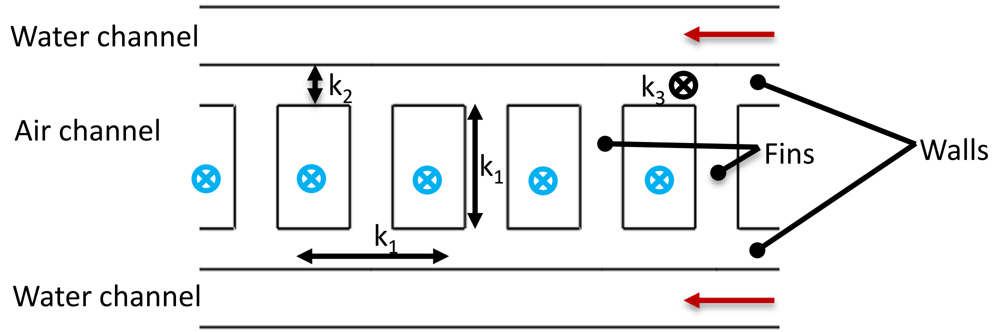


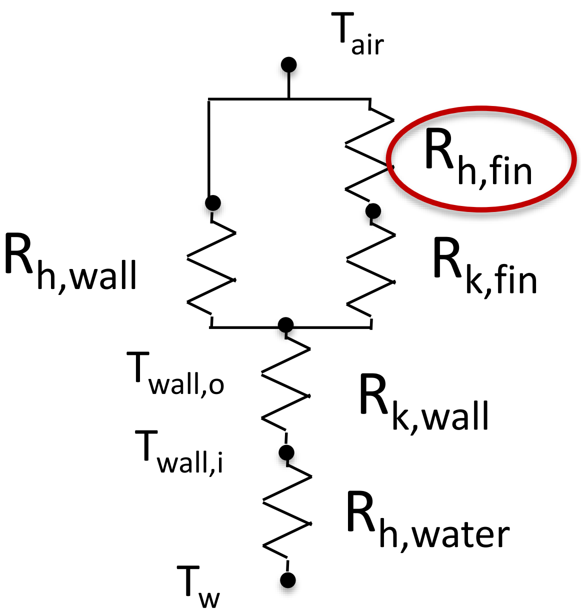
Aluminum or Polymer Air-Cooled Heat Exchangers

Corrugated aluminum



3D printed with fins

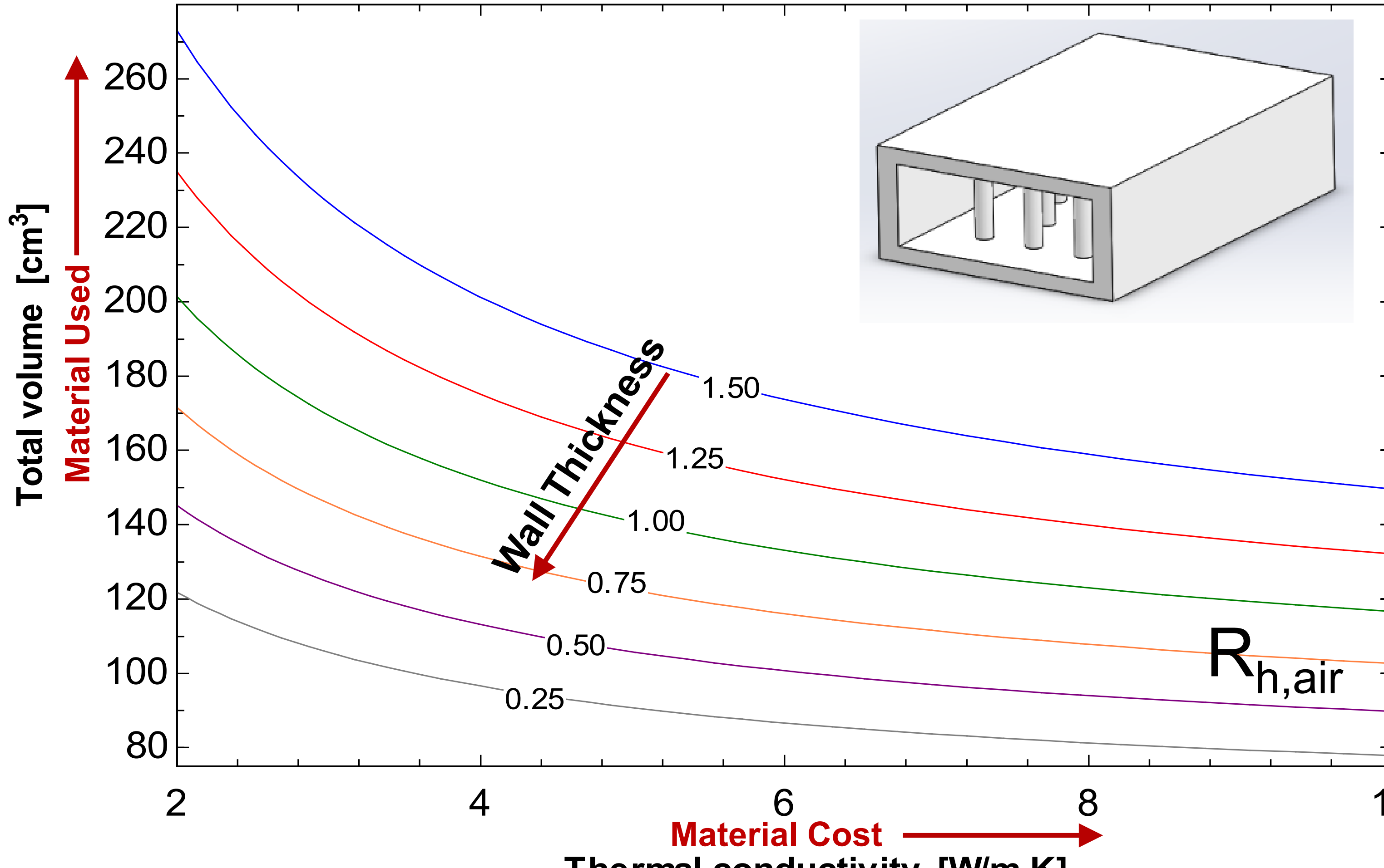




Thermal Conductivity [W/m-K]	Convection Resistance	Conduction Resistance
176 (Aluminum)	99%	1%
0.3 (PA6)	38%	62%
2 (Composite)	80%	20%

FFF Production of Air-Cooled Heat Exchangers

Material required to transfer 100 W under set conditions



Felber, R. Design, simulation, and testing of novel air-cooled heat exchangers manufacturesd by fused filament fabrication. Master's Thesis. 2017.

Project Overview

- 3 PI's, 3-5 graduate students, 4 years

HX Design/Test

- Heat exchanger model
- Air-side heat transfer surface analysis
- Design for ε, ΔP subject to constraints
- Subscale testing
- Full scale testing

properties

feature size

subscale designs

demonstrator designs

test specimens

Manufacturing

- Polymer/matrix selection
- Filament extrusion
- Material testing
- Print trials/subscale HX
- Process development
- Print demonstration HX

strength

Advanced Simulation

- G-code visualization
- Simulation of manufacturing process
- Printability
- Strength / FEA

G-code

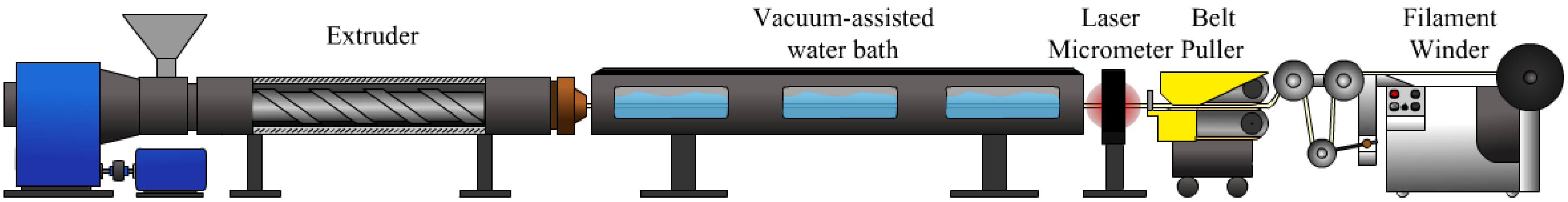
printability

Filament Extrusion

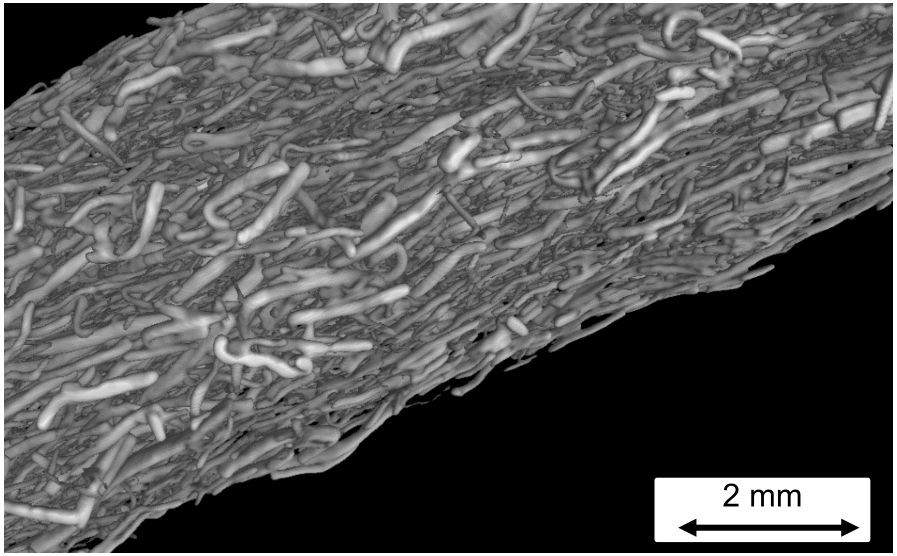
- 45 mm, 30 L/D Extrudex single-screw extruder
- 3-axis LaserLinc™ Triton331 laser micrometer: average diameter and ovality
- Leistritz ZSE 27 HSe twin screw extruder with 27-mm co-rotating, reconfigurable screws for compounding materials.

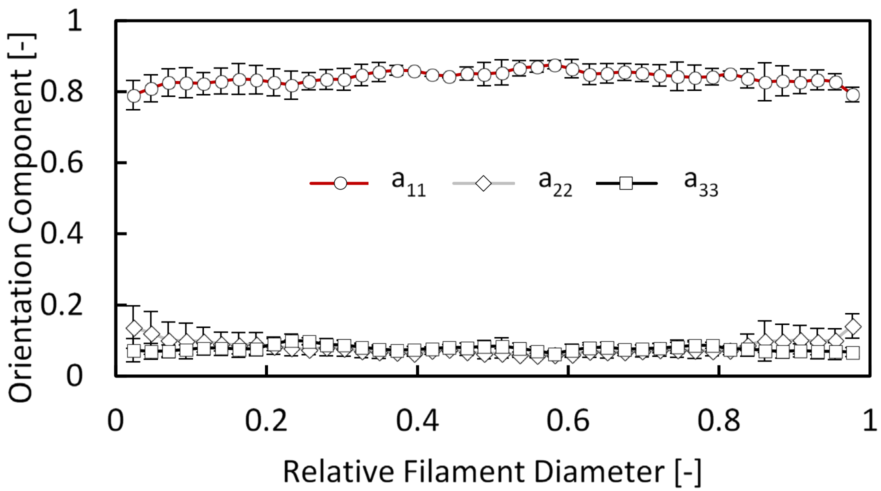
Polyamide 6 (PA6) filament with:

- Copper spheres (≤45 μm diameter) 25 %vol
- Copper fibers (30 μm diameter, ≤500 μm length) fillers, 20 %vol and 25 %vol

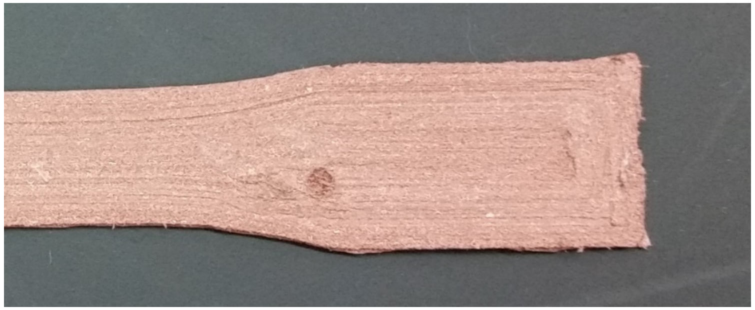


Material Characterization





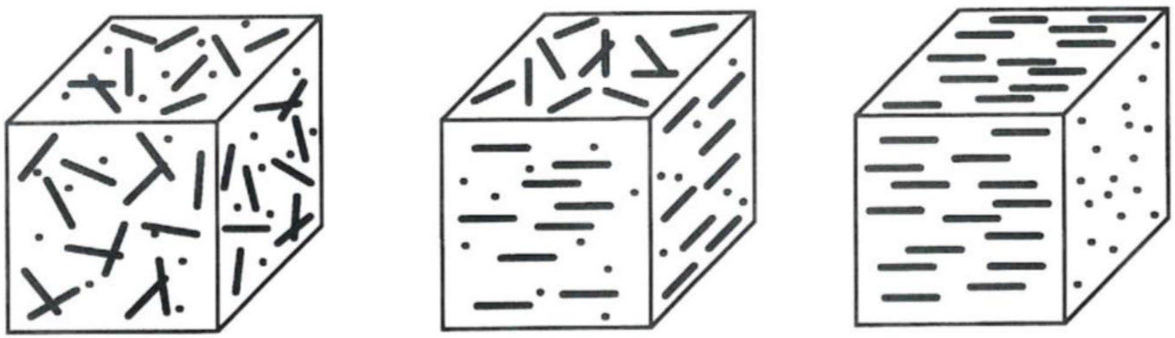
- Thermal diffusivity
  - 1-, 2-, and 3-direction
- Specific heat capacity
- Density and filler content
- Strength and elongation at break
- Micro-computed tomography (µCT)
  - 5-10 µm resolution



Fiber Orientation Analysis

Fiber orientation can be quantified through µCT analysis.

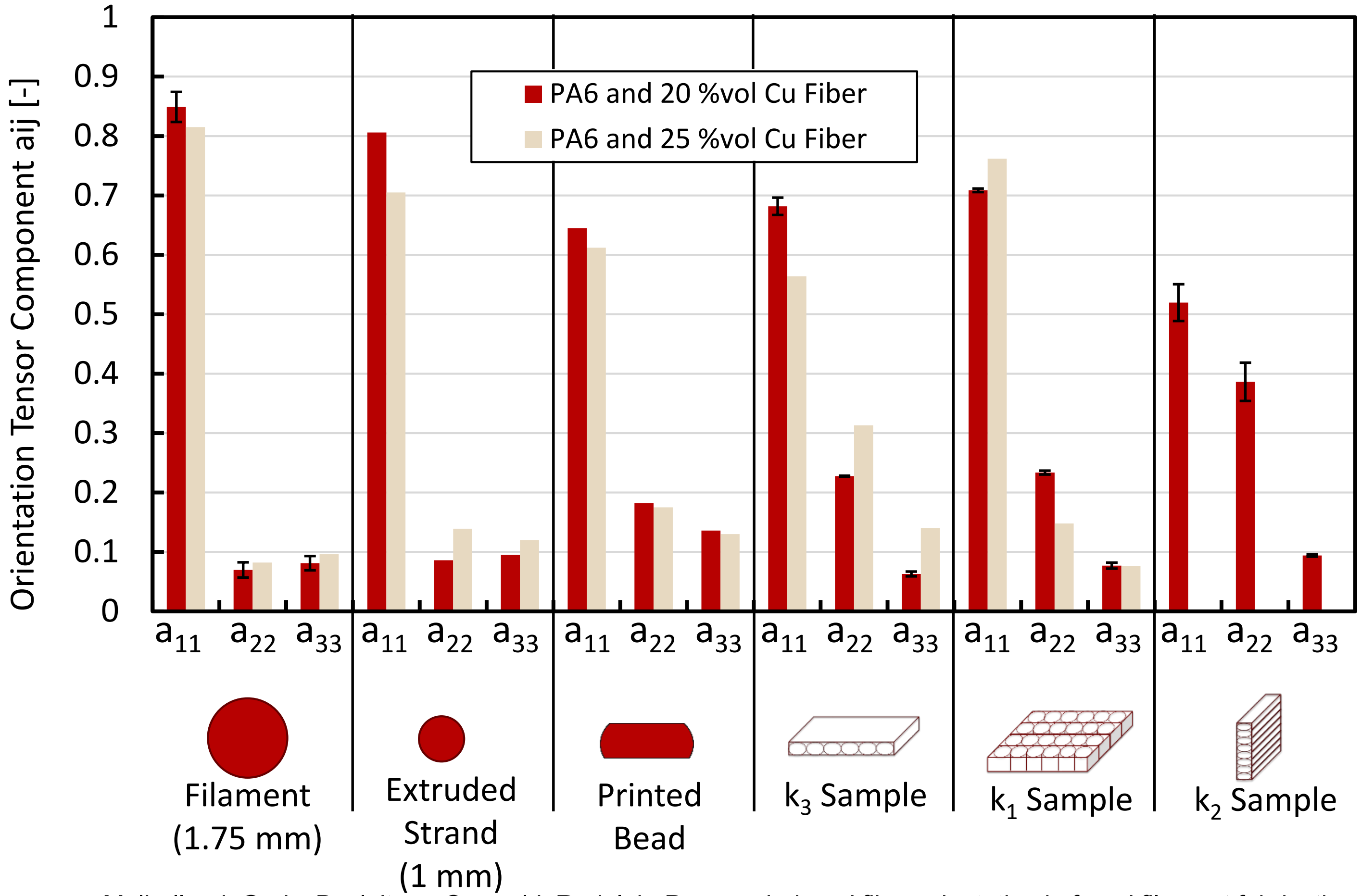
Orientation is represented as a tensor, with the diagonal components representing the average degree of orientation in the 3 principal directions.



$$\begin{bmatrix} 1/3 & 0 & 0 \\ 0 & 1/3 & 0 \\ 0 & 0 & 1/3 \end{bmatrix} \qquad \begin{bmatrix} 1/2 & 0 & 0 \\ 0 & 1/2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

H. Stoll, “Modellierung und Simulation des Spritzprägeverfahrens mit kurz-faserverstärkten Thermoplasten,” Dr.-Ing. Dissertation, Universität Stuttgart, 2011.

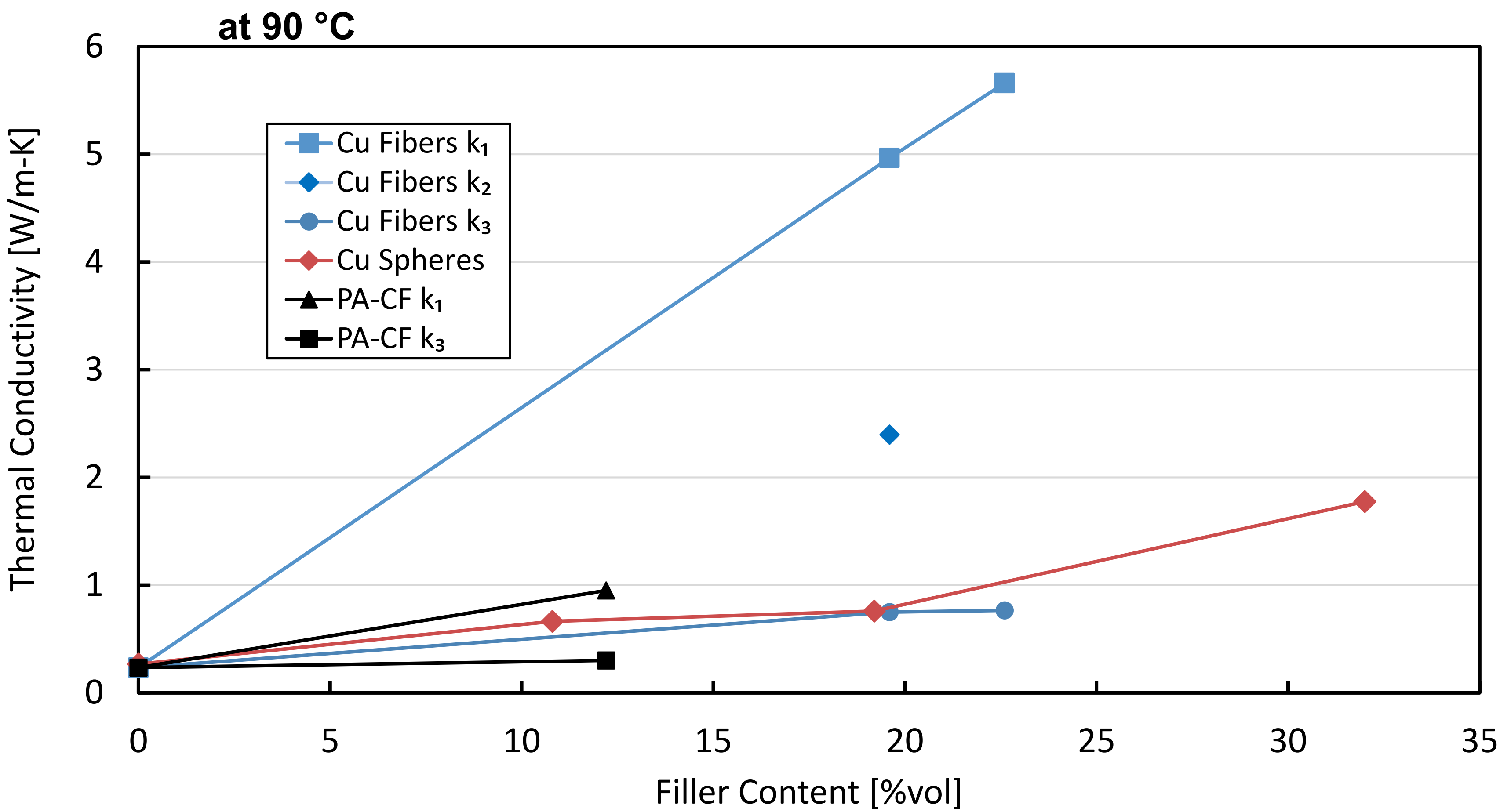
Fiber Orientation Analysis



Mulholland, Goris, Boxleitner, Osswald, Rudolph. Process-induced fiber orientation in fused filament fabrication. J. Compos. Sci. 2018.

2 Material and Characterization

The filler shape and content have a strong effect on thermal conductivity.



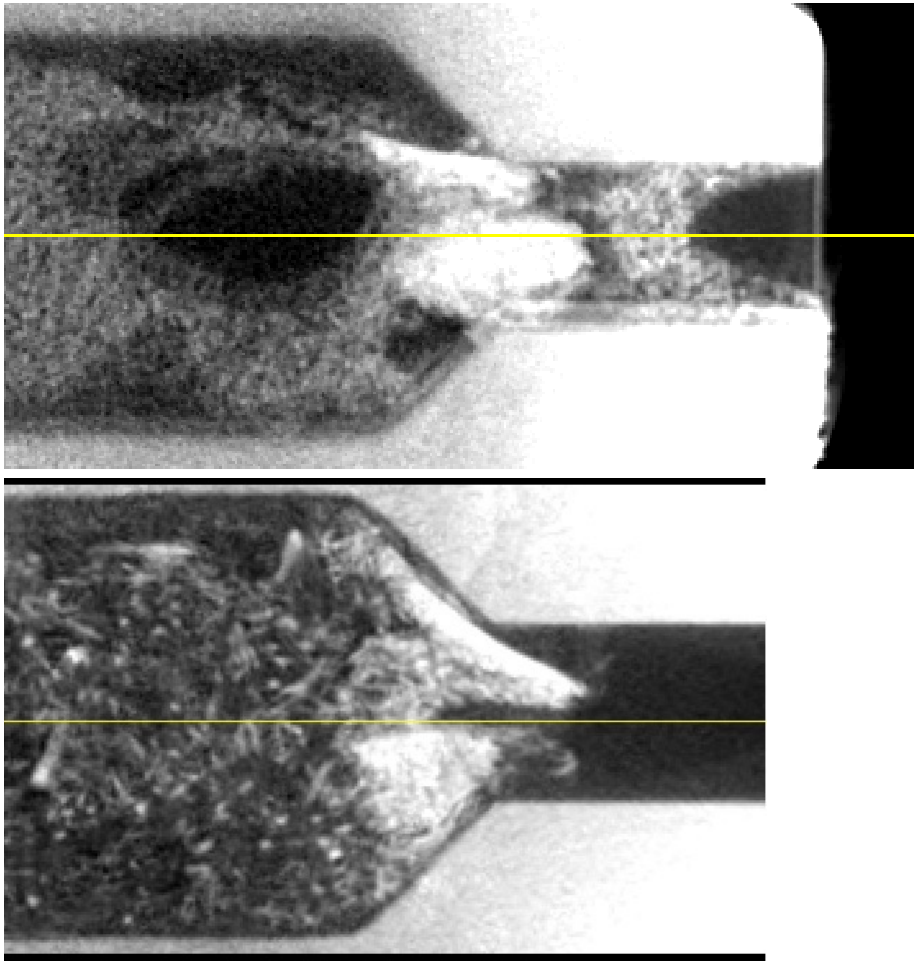
Material Characterization

- μCT shows an issue with highly filled materials in FFF, even with a large (0.8 mm) nozzle.

33 %vol copper spheres
95% Spheres < 45 μm diameter

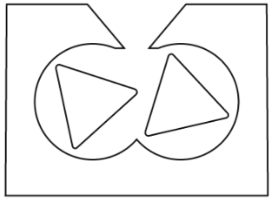
Nozzle diameter: 800 μm
Constriction: ~80°

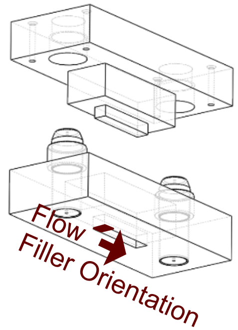
33 %vol copper fiber
Fiber diameter: 30 μm
Fiber length: ≤3 mm



Scan Resolution: 13 μm

Material Development





Resin

+

Filler

Brabender Batch Mixer

Compression Molding

Clogging/ Flowing Test

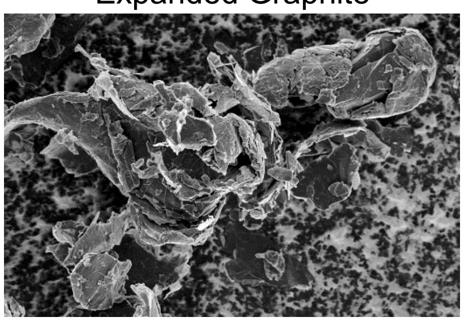
Tensile Test

Thermal Conductivity Test

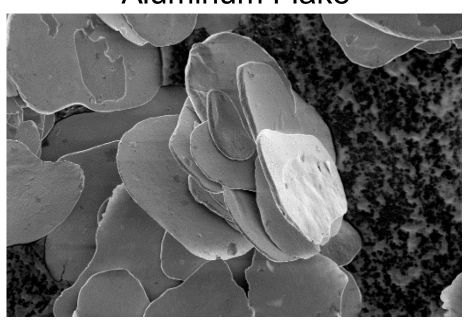
Twin Screw Extrusion (Filament)

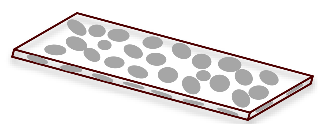
FFF

Expanded Graphite



Aluminum Flake

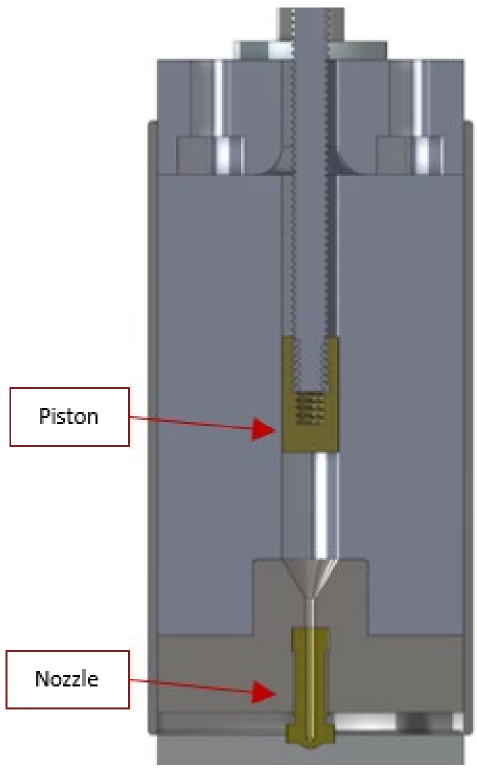


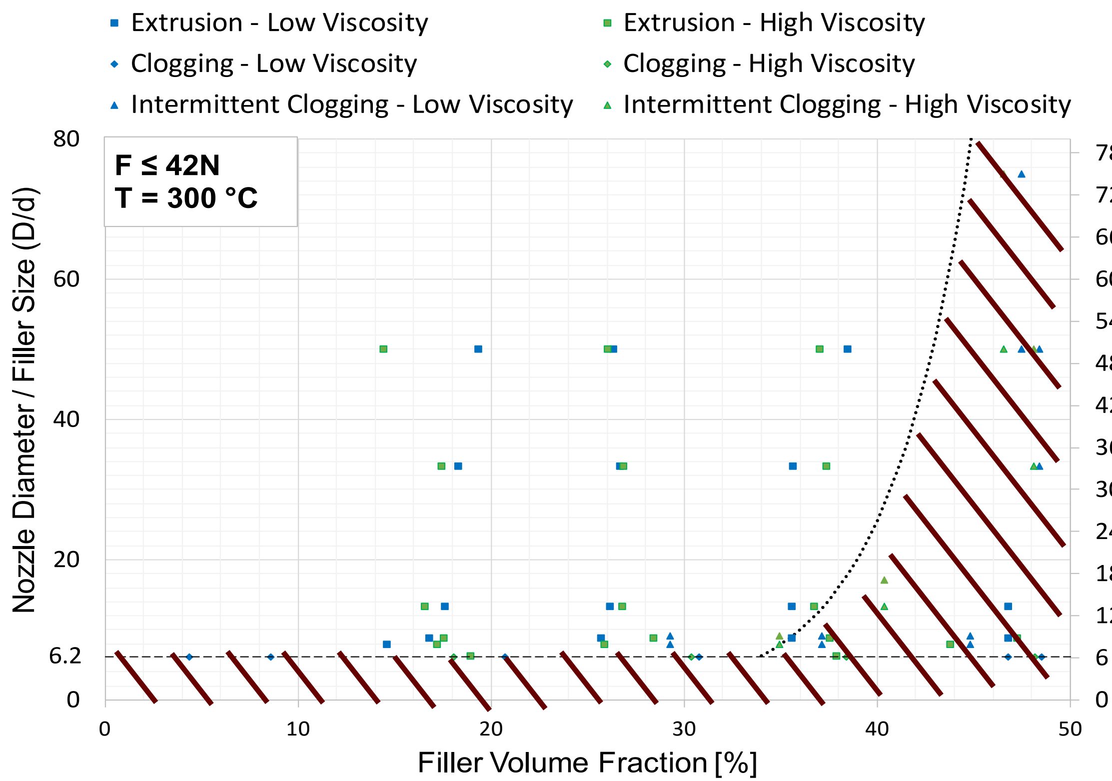


Ettl. Experimental validation of thermally conductive composites for fused filament fabrication. M.S. thesis. 2018.

Clogging Tests

- Dry mix small batches fillers with cryogenically ground polymer powder.
- Run clogging tests on the Nozzle Flow Tester
- Spherical and platelet fillers establish distinct safe zones for extrusion.
  Fibers were difficult to measure.

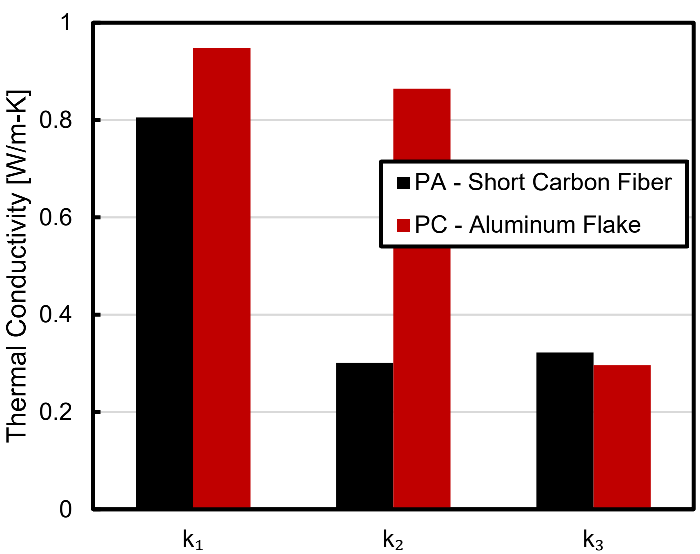


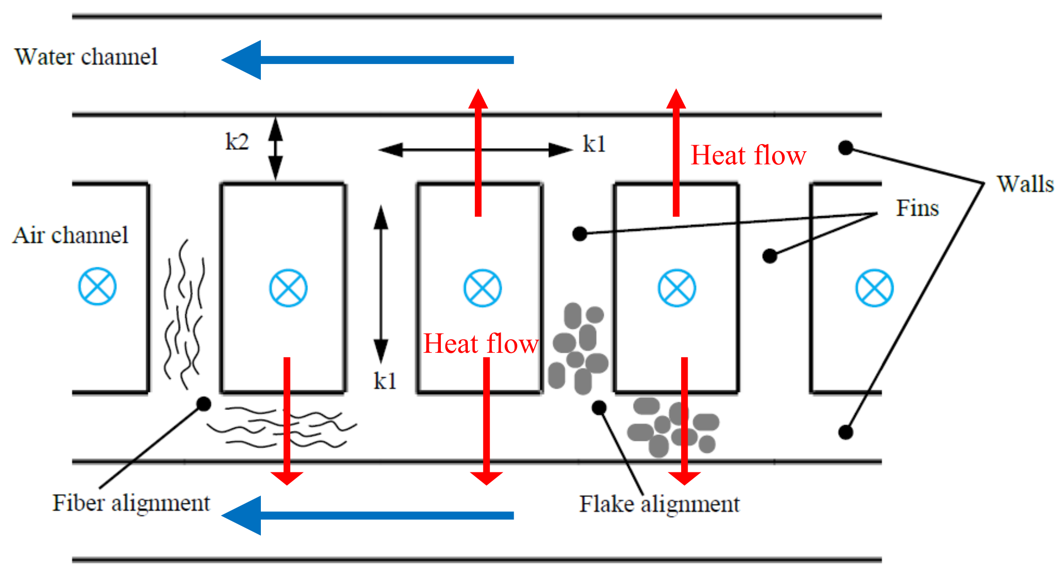


Beran, Mulholland, Henning, Rudolph, Osswald. Nozzle clogging factors during fused filament fabrication of spherical particle filled polymers. J. Add. Mfg. 2018.

Fused Filament Fabrication

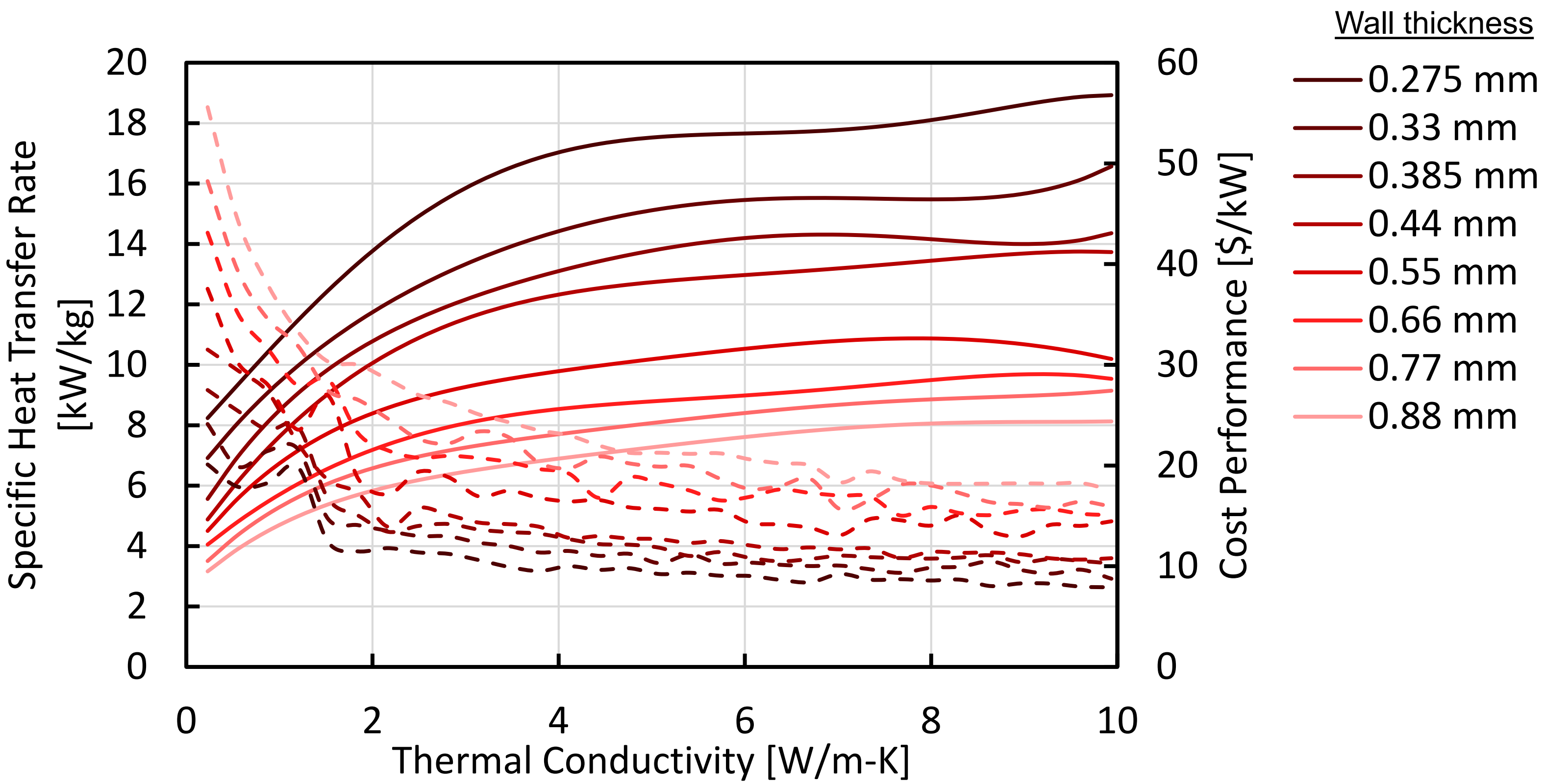
- Fused filament fabrication (FFF) allows the use of thermally conductive polymer composites.
- A polycarbonate (Makrolon) and aluminum flake composite was developed.
- Fibers minimally improve thermal conductivity through thin walls. Flakes provide conductivity in two directions.
- Thermal conductivity and watertightness strongly depend on the toolpath.





Thermal and Cost Performance

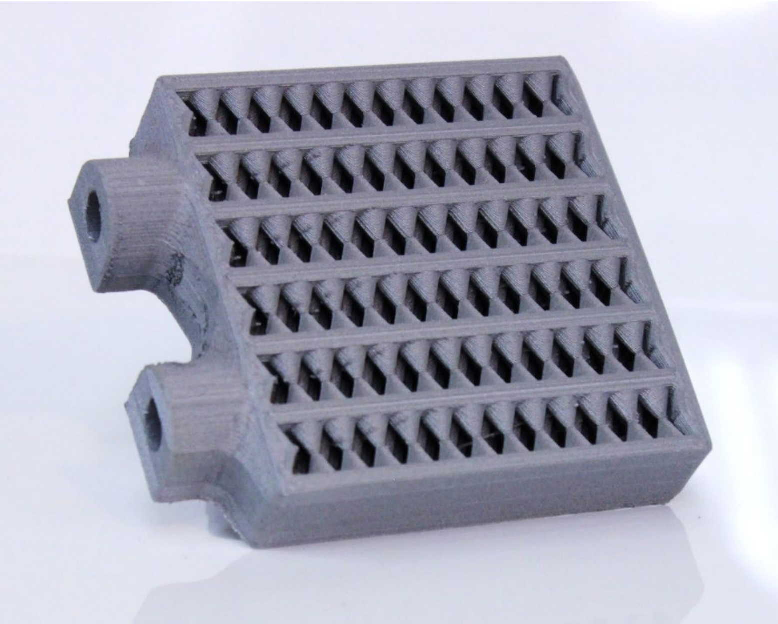
- Thermal performance was modeled by thermal resistance networks utilizing the pressure drop / heat transfer correlations simulated by computational fluid dynamics.
- Performance increases with thermal conductivity, and the cost continuously decreases, despite the increased material cost.

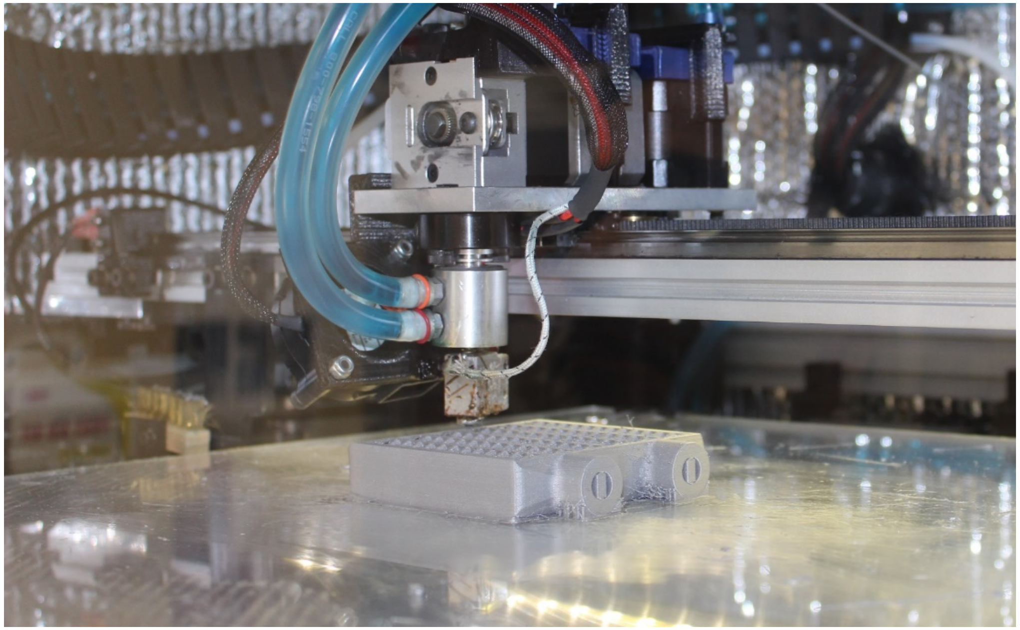


Additive Manufacturing of Heat Exchangers

- Thin-walled structures with effective fin design improve the heat transfer rate.
- Controlling toolpath is essential to achieving watertightness at operating pressure.
- Polymer composite air-cooled heat exchangers are much better than aluminum or stainless steel versions on a weight basis. They are competitive on a cost and heat transfer basis.

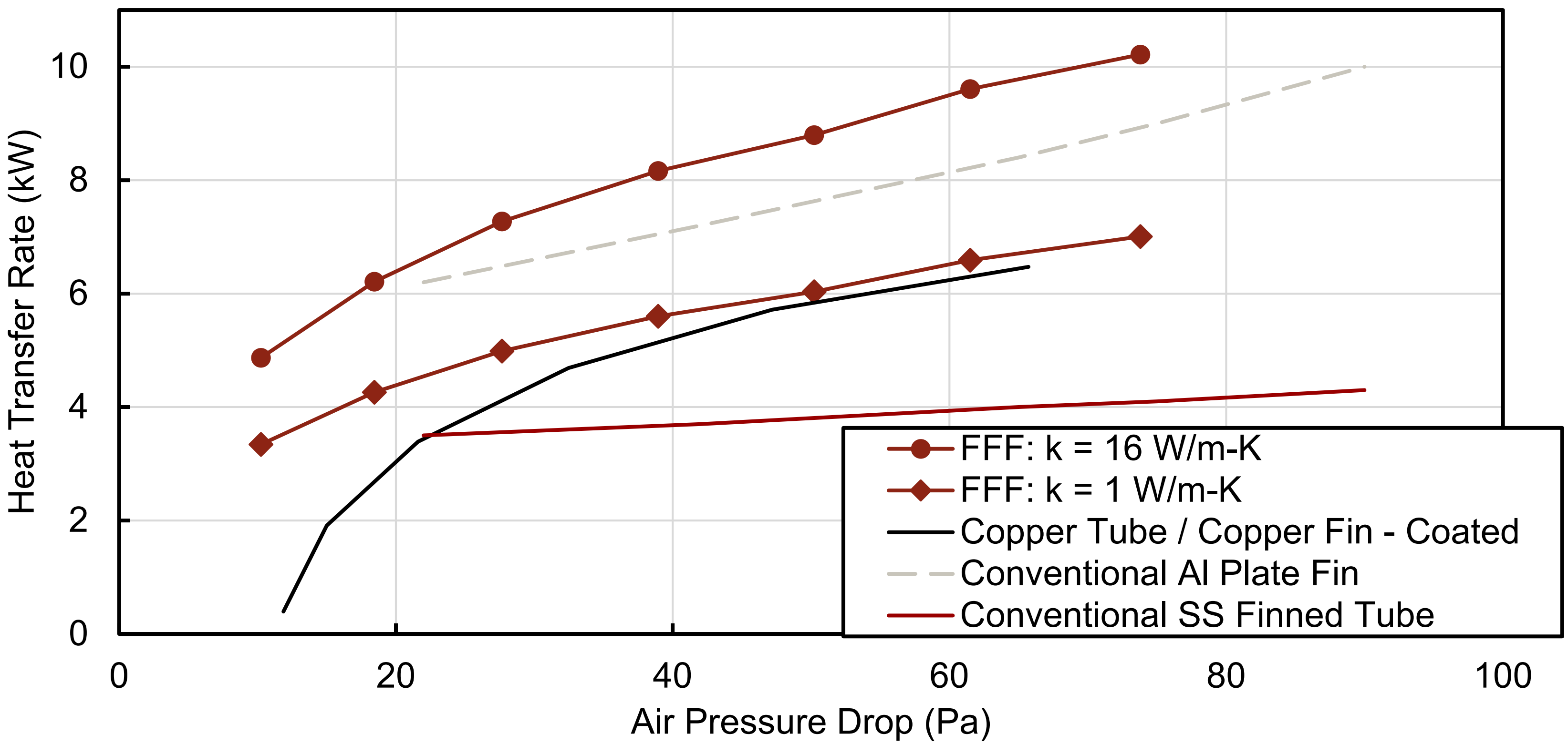
Tapered Fin Design





Additive Manufacturing of Heat Exchangers

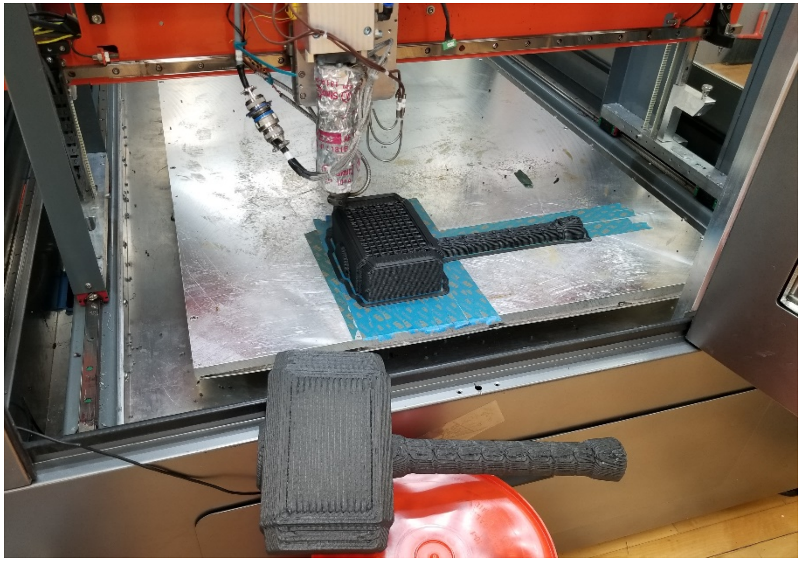
- Test data for the PC-Al (1 W/m-K) composite, stainless steel, and two conventional heat exchangers are below. Based on testing with DMLS, a polymer composite with 16 W/m-K would perform at least 10% better than conventional aluminum HXs.



Current Work

- We are now using highly filled polymer compounds to produce heat exchanger test specimens with a pellet extrusion additive manufacturing machine.
- We're also working with materials such as BASF Ultrafuse 316LX sinterable stainless steel polymer composite.

Cosine Additive
Pellet Extruder



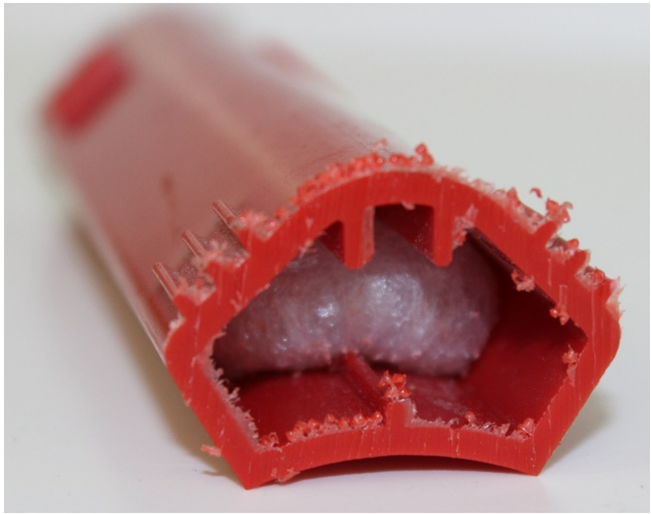
Covestro Makrolon® TC8030
Graphite - PC

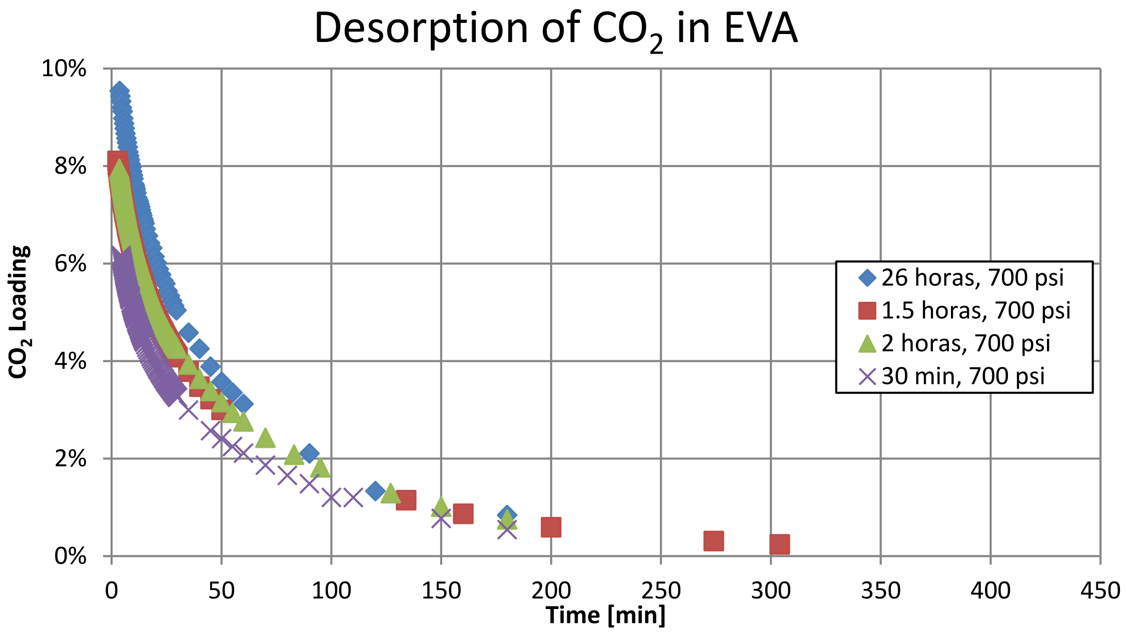
Institute for Plastics and Rubber – ICIPC, Colombia

- Patent search and landscape analysis
  - Dispensing devices for controlling mosquito-borne disease
  - Active and passive smart packaging
  - Packaging for prolonging fruit/vegetable shelf life
  - Injection foaming
- Experiments and Seminars
  - Energy efficiency in injection molding
  - Design of experiments
- Injection molding simulation
  - CADMould
  - IM of autoparts
  - Design of experiments – analysis of tolerance compliance

Foam Injection Molding

- At the ICIPC in Colombia, we developed a technique to inject foamed polymer into a polymer housing, disclosed in US Patent Application US20150361239A1.
- The goal was to improve impact resistance of shells at reduced weight, while maintaining recyclability.
- In order to avoid foaming processes that were expensive to license, we experimented with physical impregnation through batch processing of pellets under pressure.





Carvajal, López, Hernández, Mulholland, Peña. Lower temperature process for integrating a polymeric foam with a polymeric body. US20150361239A1.

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