Karlsruhe Institute of Technology

Institute of Vehicle System Technology
Division Lightweight Engineering
Digitalization in Lightweight Design

Homogenization of the Anisotropic Thermal Conductivity of Mesostructures in Material Extrusion

Hof, L. | Frölich, F. | Wittemann, F. | Kärger, L.

Karlsruhe Institute of Technology (KIT), Institute for Vehicle Systems Technology, Rintheimer Querallee 2, Karlsruhe, 76131, Germany

Motivation

- Accurately modelling the thermal history during the MEX process is key to predict interlayer bonding, crystallinity, residual stresses and warping.
- Due to the porous mesostructure, properties such as the apparent thermal conductivity are anisotropic and reduced compared to the monolithic material.
- The apparent thermal conductivity is specific to the exact mesostructure. Some literature suggests reduced thermal conductivity in the interfaces between beads [1,2].

Material and Methods

- Material: BASF Ultrafuse PLA filament.
- Machine: Anisoprint Composer A4
- Infill: unidirectional beads
- Modelling: 1D analytic model, 2D FE model
- Experimental: Transient Hot Bridge (THB) method [3] and measurements according to ASTM D5470 [4]

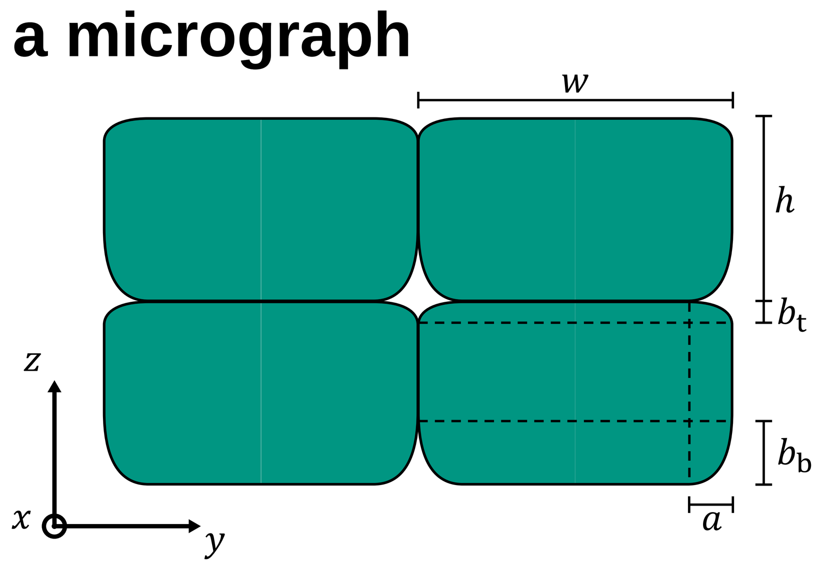
Deriving a simplified parametric Geometry from a micrograph

Assumptions

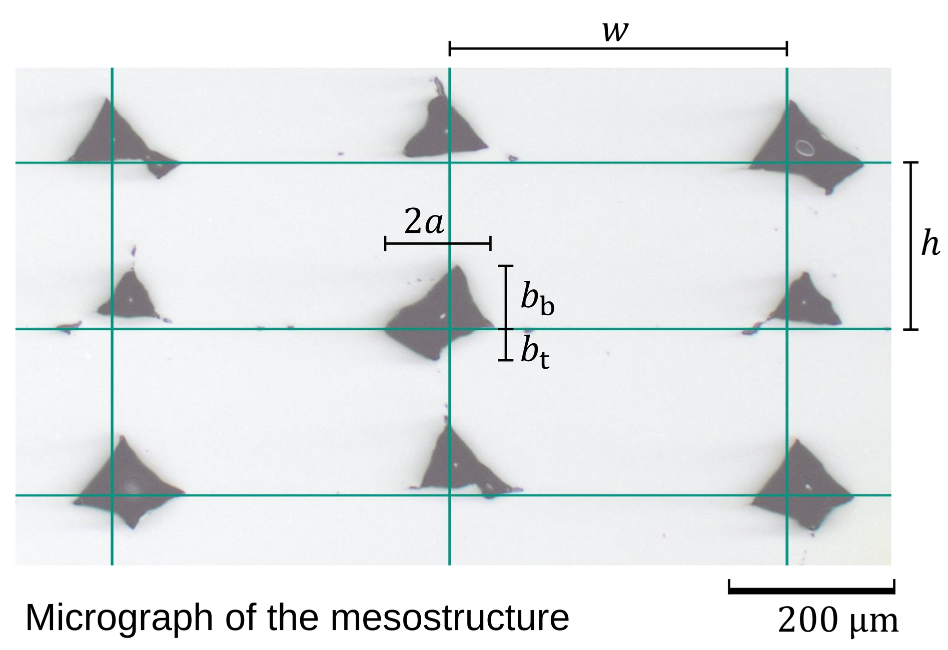
- Identical beads arranged in a grid
- Symmetric cross sections
- Corners are quarter ellipses of equal width a

→ Idealized Geometry described by five parameters

→ The parameters are set to averages, measured from micrographs of the structure.



Idealized parametric mesostructure



Micrograph of the mesostructure

Analytic approach

- The thermal conductivity of the PLA filament was measured using the THB method on a molded sample to be $\kappa_\mathrm{p} \approx 0.196\,\frac{\mathrm{W}}{\mathrm{m\,K}}$.
- ***x*-direction** - weighing the polymer and air with their relative cross-sectional areas:
  $\kappa_x = \kappa_\mathrm{p} A_\mathrm{rel,\,p} + \kappa_\mathrm{air} A_\mathrm{rel,\,air}$
- ***y*-direction** - weighing the polymer and air with their relative height:
  $R_y = \int_0^w \frac{1}{\kappa_\mathrm{p}\frac{h_\mathrm{p}(y)}{h} + \kappa_\mathrm{air}\left(1-\frac{h_\mathrm{p}(y)}{h}\right)}\,dy + R_{\mathrm{i},\,y} \qquad \kappa_y = \frac{w}{R_y}$
- ***z*-direction** - analogous to y-direction:
  $R_z = \int_0^h \frac{1}{\kappa_\mathrm{p}\frac{w_\mathrm{p}(z)}{w} + \kappa_\mathrm{air}\left(1-\frac{w_\mathrm{p}(z)}{w}\right)}\,dz + R_{\mathrm{i},\,z} \qquad \kappa_z = \frac{h}{R_z}$

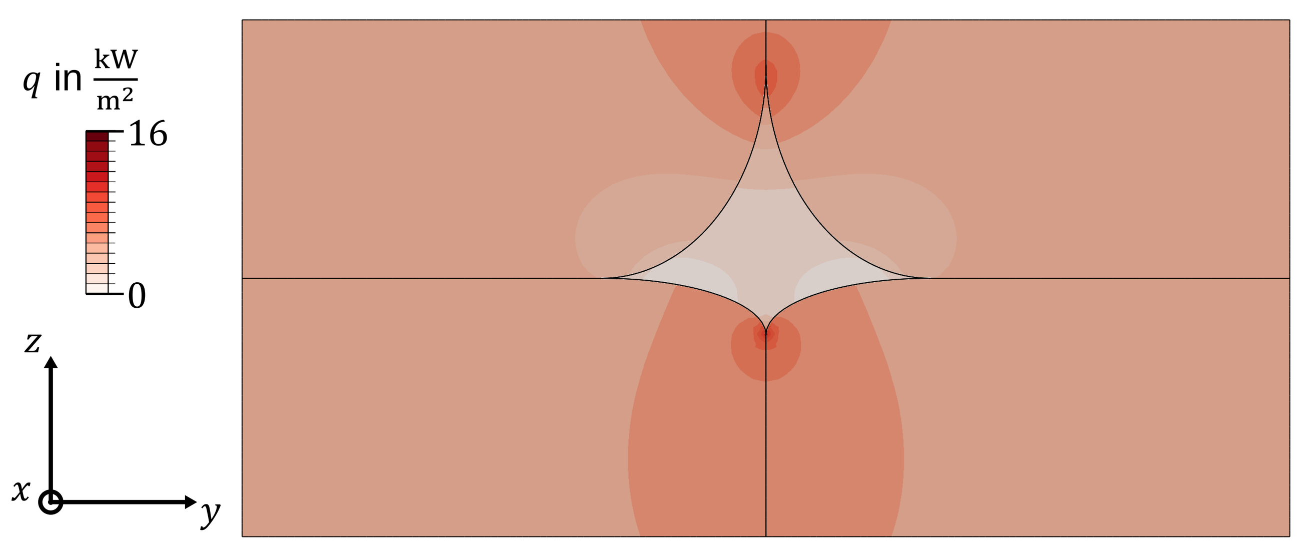
→ Without any thermal resistance in the interface $R_\mathrm{i} = 0$, this approach yields similar results in all directions:

$$\boldsymbol{\kappa} \approx \begin{pmatrix} 0.1900 \\ 0.1887 \\ 0.1894 \end{pmatrix} \frac{\mathrm{W}}{\mathrm{m\,K}} \triangleq \begin{pmatrix} 96.95\ \% \\ 96.25\ \% \\ 96.63\ \% \end{pmatrix} \kappa_\mathrm{p}$$

Two-dimensional FE-model

- A 2D-model allows to capture the geometry's influence.
- The conductivity is calculated from the flux in one plane of an RVE with a temperature gradient applied to it.
- For $R_\mathrm{i} = 0$ and using the x-value from the analytic approach, this yields:

$$\boldsymbol{\kappa} \approx \begin{pmatrix} 0.1900 \\ 0.1829 \\ 0.1820 \end{pmatrix} \frac{\mathrm{W}}{\mathrm{m\,K}} \triangleq \begin{pmatrix} 96.95\ \% \\ 93.46\ \% \\ 93.00\ \% \end{pmatrix} \kappa_\mathrm{p}$$

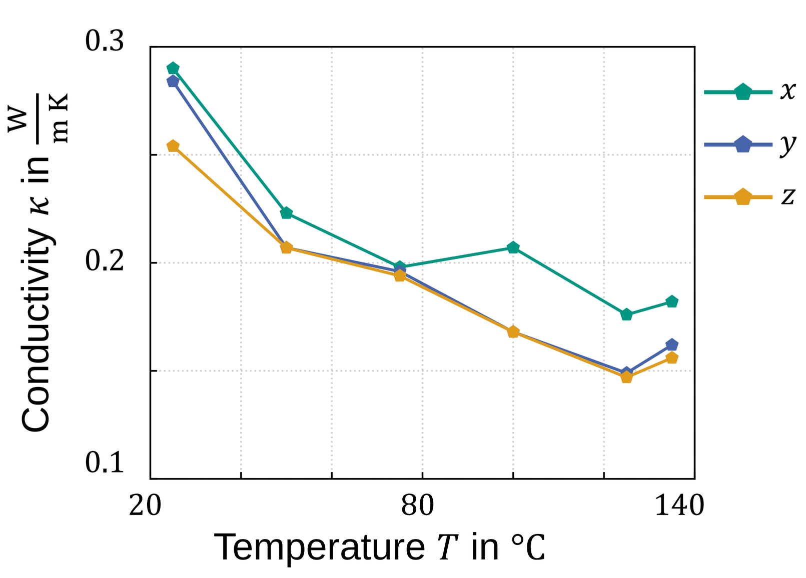


Heat flux within the mesostructure for a temperature gradient in the y-direction

Measurements

- Directional measurements on printed samples according to ASTM D5470 yield inconclusive and unexpectedly high results.
- THB measurements on printed samples suggest a reduction compared to the monolithic material of at most 12.7 %.

Measured conductivity of printed samples



Conclusion

- The one-dimensional analytic approach should be sufficient for the x-direction.
- The 2D FE model allows the approximation in the y- and z-direction and captures the significant influence of the geometry.
- Additional thermal resistance in the interface can easily be incorporated into both models.
- Reliable measurements for validation and to quantify the resistance in the interface are however challenging to obtain.

[1] Elkholy, A., Rouby, M. & Kempers, R. Characterization of the anisotropic thermal conductivity of additively manufactured components by fused filament fabrication. Progress in Additive Manufacturing 4, 2019.

[2] Prajapati, H., Ravoori, D., Woods, R. L. & Jain, A. Measurement of anisotropic thermal conductivity and inter-layer thermal contact resistance in polymer fused deposition modeling (FDM). Additive Manufacturing 21, 2018.

[3] DIN-Normenausschuss Kunststoffe (FNK) & DIN-Normenausschuss Bauwesen (NABau). DIN EN ISO 22007-2: Klebstoffe - Bestimmung der Wärmeleitfähigkeit und der Temperaturleitfähigkeit – Teil 2: Transientes ebenes Wärmequellenverfahren (Hot-Disc-Verfahren). DIN e.V., 2022.

[4] D09 Committee. ASTM D5470 - 17: Test Method for Thermal Transmission Properties of Thermally Conductive electrical Insulation Materials. Technical report, ASTM International, 2017.

Lukas Hof, M.Sc.
lukas.hof@kit.edu
www.fast.kit.edu/english/lbt

FAST Institute of Vehicle System Technology