Evaluation of the temperature history during extrusion based additive manufacturing

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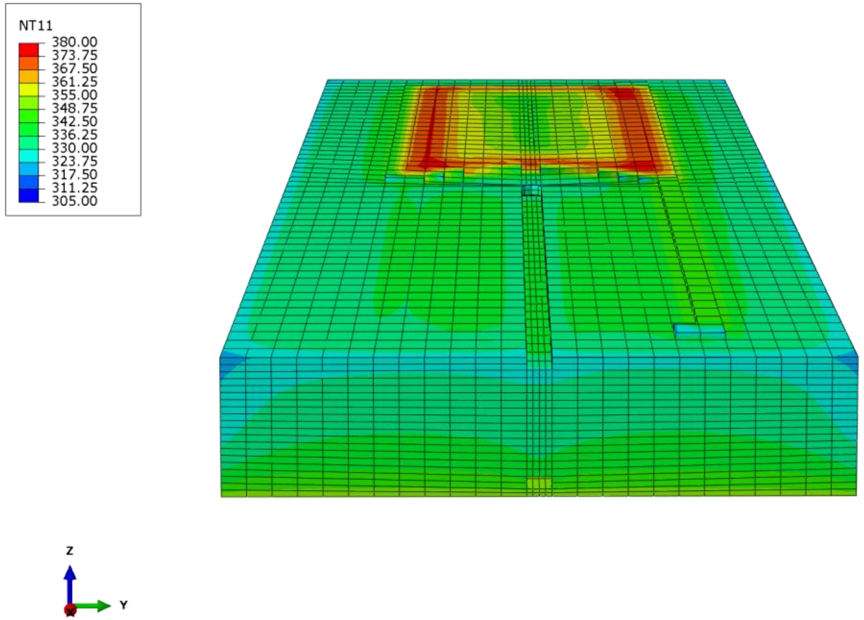
Motivation

Agenda

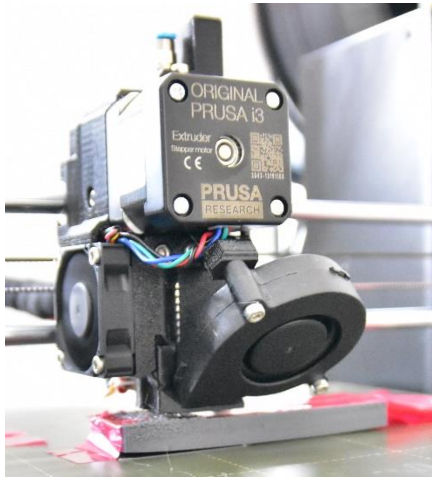
- FDM process simulation
- Validation of the part temperature
- Simulation of the part crystallinity
- Summary and next steps

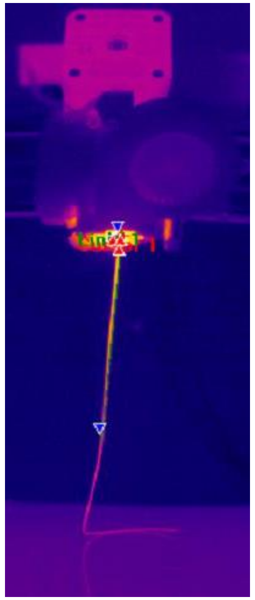


FDM process simulation - Motivation

Key Challenges and important topics:

- Geometric conformity
- Residual stress management
- Build failure
- Inhomogeneous material properties
- process-dependent material anisotropy
- In-deep process understanding





Simulation of the additive extrusion process is a challenging task:

- Phenomena occur over multiple length scale
- Phenomena occur over multiple time scale
- Multiphase problem
- Missing validation

Validation of the part temperature

Objective:

– How good is the forecast of the temperature history?

Test set-up:

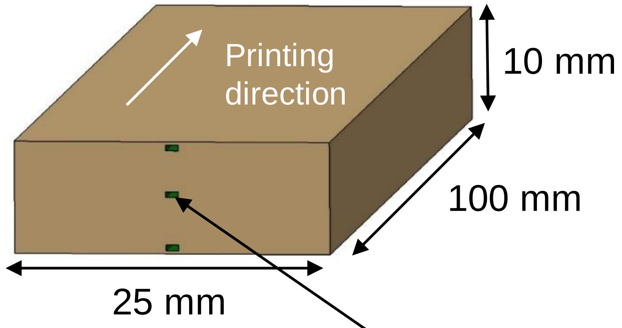
– Printer: Prusa MKi3

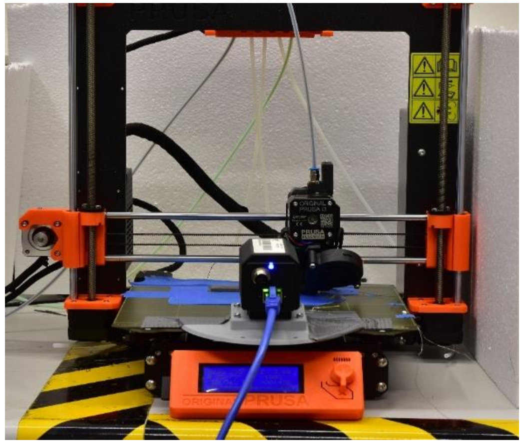
– Material: PETG

– Nozzle temperature: 245°C; Print bed temperature: 80°C

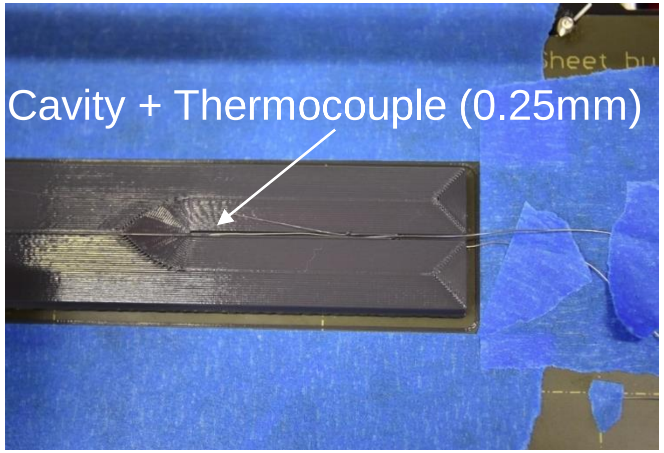
– Printing speed: 2300 mm/min; infill:100%

Test geometry

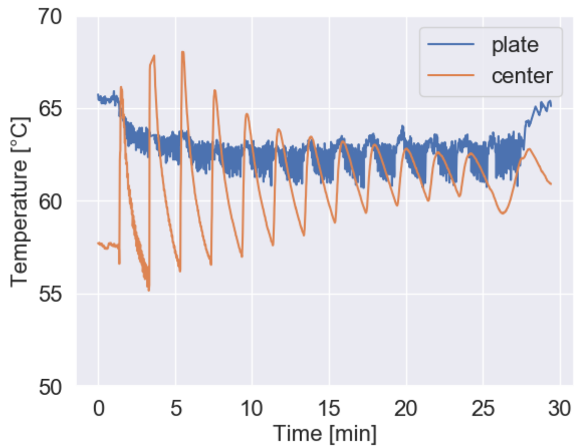




Applied Prusa Printer



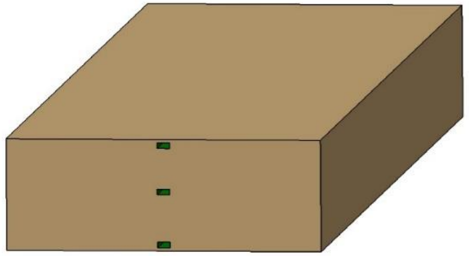
Integration of the thermocouple

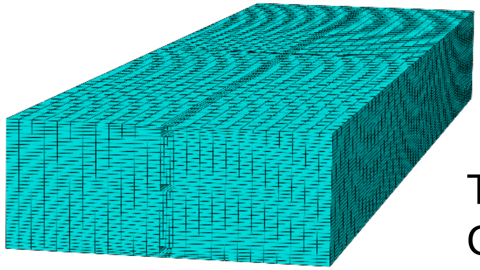


Measured temperatures

FDM process simulation – Basic concept

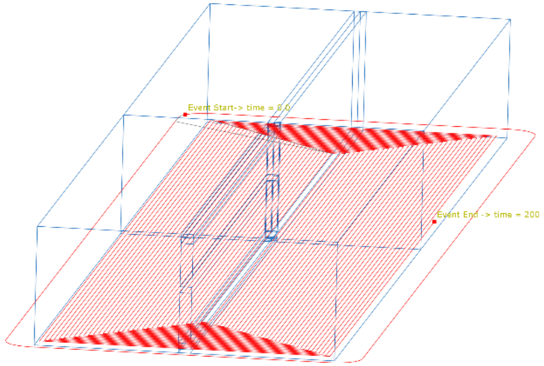
CAD

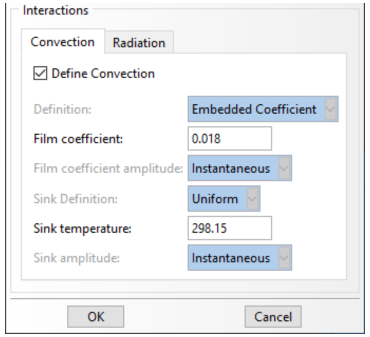




Meshing

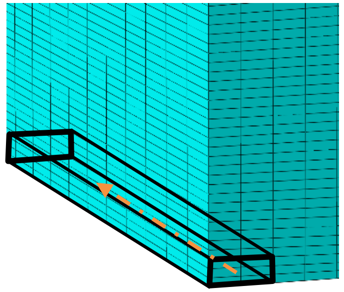
ToolPath Conversation
G-Code->Event-Series





Thermal boundary conditions

Progressive Element Aktivation

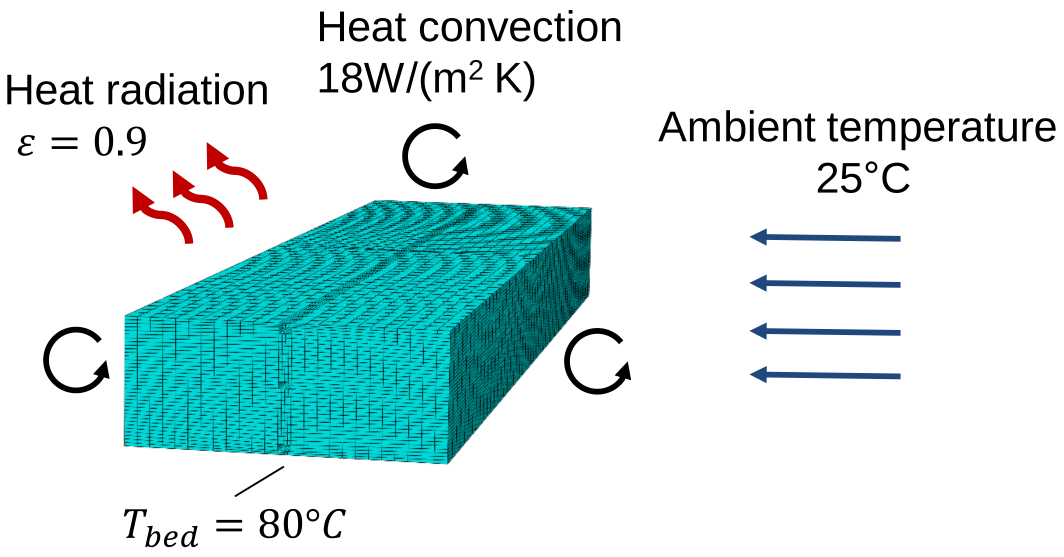


Analysis

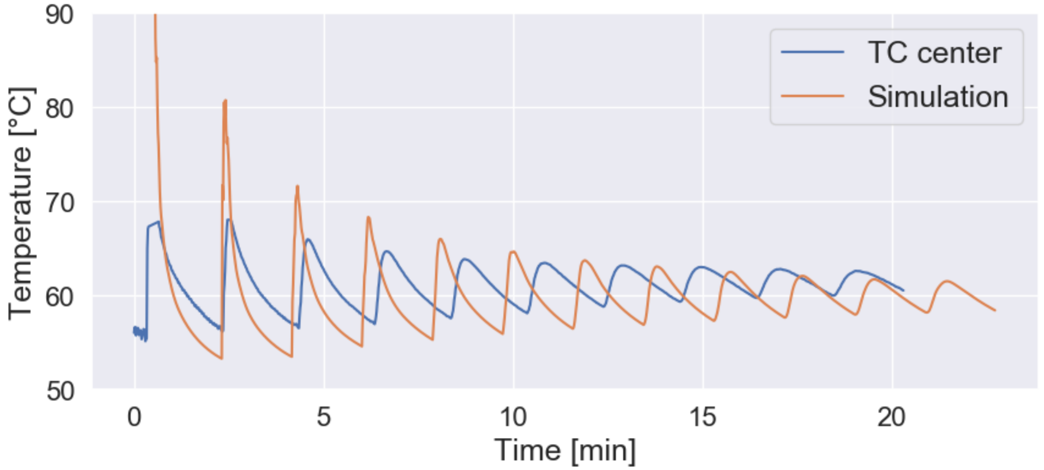
FDM process simulation

Thermal boundary conditions:

- Initial element temperature: 245°C
- Assumption: constant thermal boundary conditions



Results:

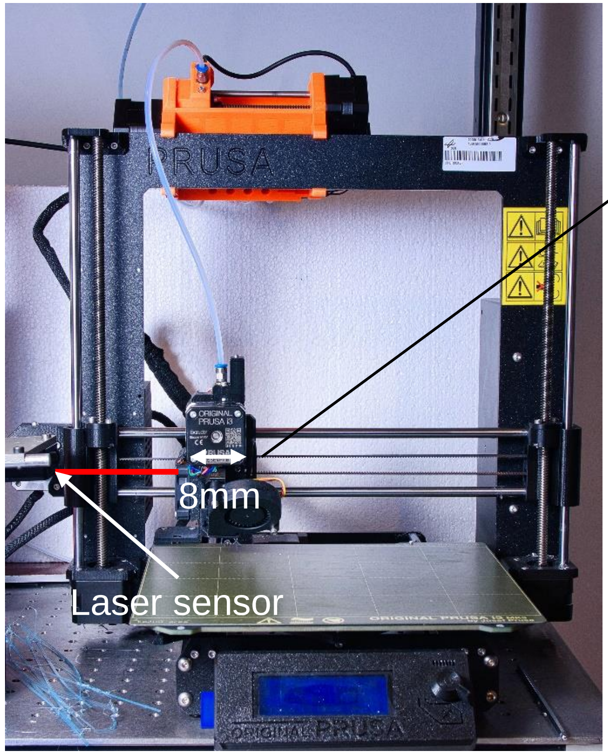


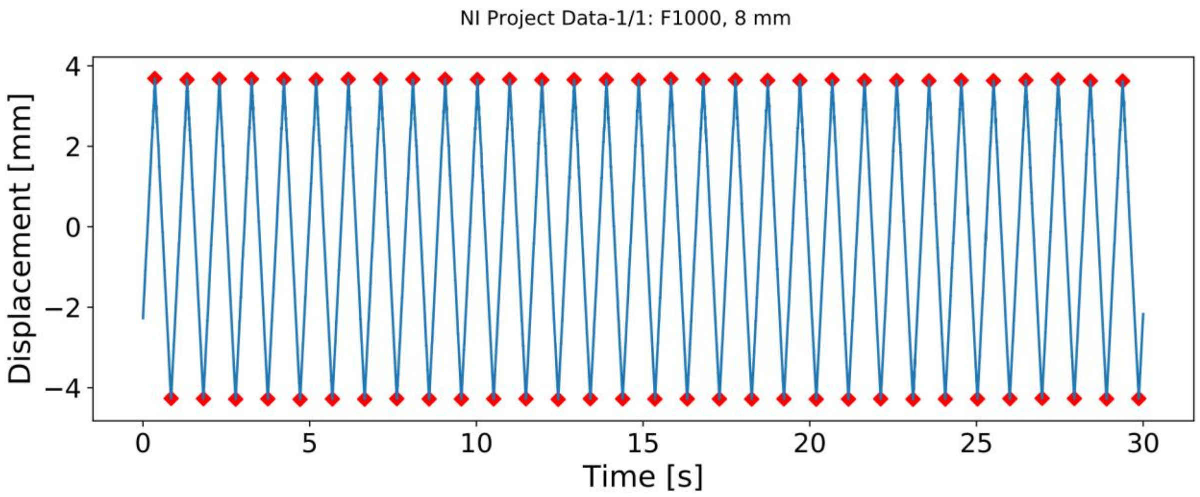
Simulated process is faster despite identical G-code.

Are there deviations between the "planned" velocities and "As-Built"-velocities?

Verification of printer velocity

- Measurement of print head kinematics via laser triangulation





Velocity [mm/min]	Target [mm/s]	Real [mm/s]
F1000	16.66	16.23
F2000	33.33	29.91
F3000	50	37.21
F4000	66.66	45.31
F5000	83.3	48.02
F7000	116.67	50.41

Acceleration and Decelaration cause delays between predefined and real velociy!

Crystallization kinetics

Objectives:

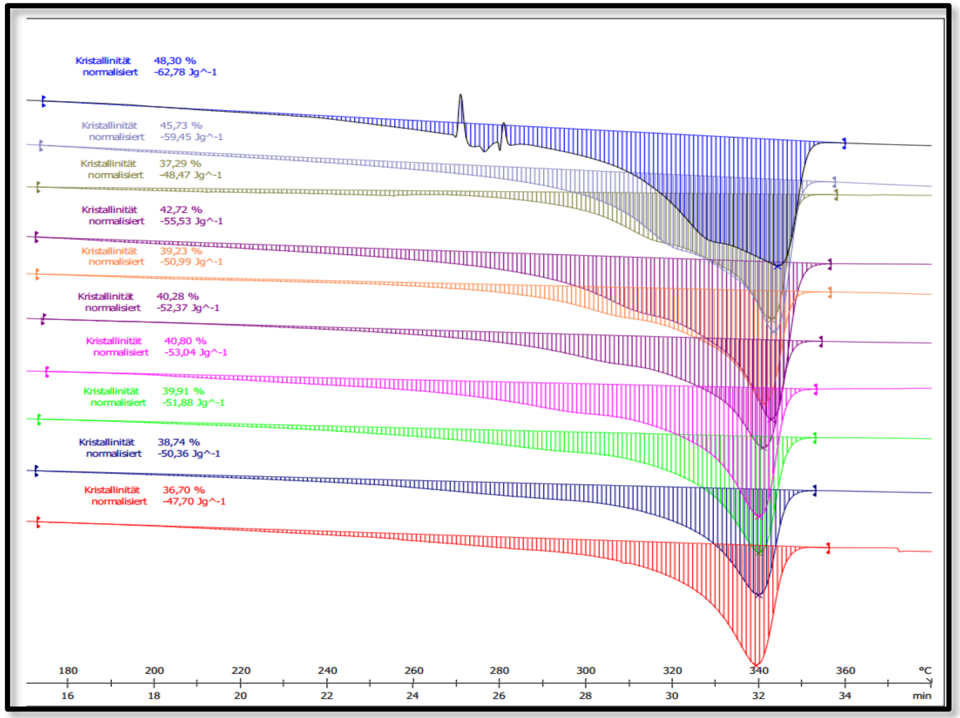
- Part quality evaluation
- Process optimization

Experimental characterization:

- DSC (up to 100K/min) or Flash-DSC (up to 5000 K/min)
- Real cooling rates up to 3000K/min ->Flash-DSC required

Integration into simulation:

- Mostly phenomenological approaches
- Integration by user subroutines

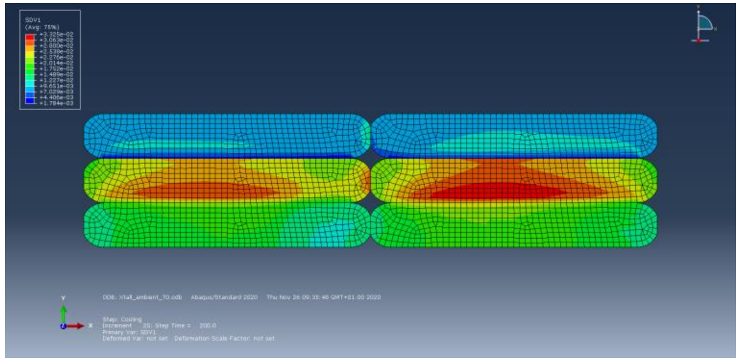


Crystallization kinetics

- Modelling procedure

[Brenken, 2017]

$$X_{vc} = X_{vc\infty}(w_1 F_{\vartheta 1} + w_2 F_{\vartheta 2})$$
$$F_{\vartheta i} = 1 - e^{\left(-\int_0^t k(T) n_i \tau^{(n_i - 1)}\right)}, i = 1,2$$
$$k(T)_i = C_{1i} T e^{-\left(\frac{C_{2i}}{T - T_g + T_{add,i}} + \frac{C_{3i}}{T(T_{m,i} - T)^2}\right)}, i = 1,2$$

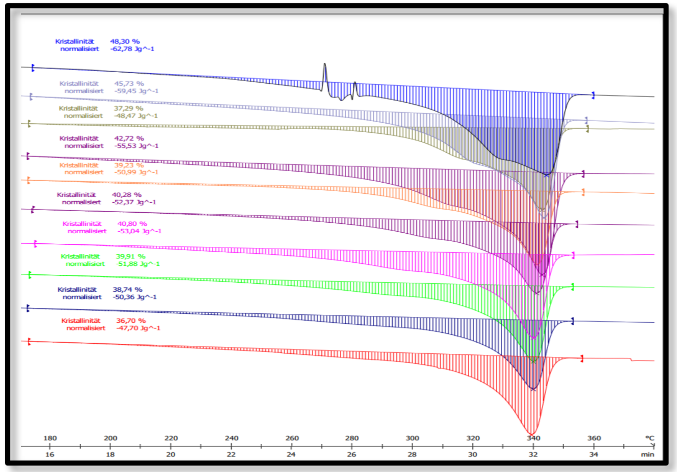


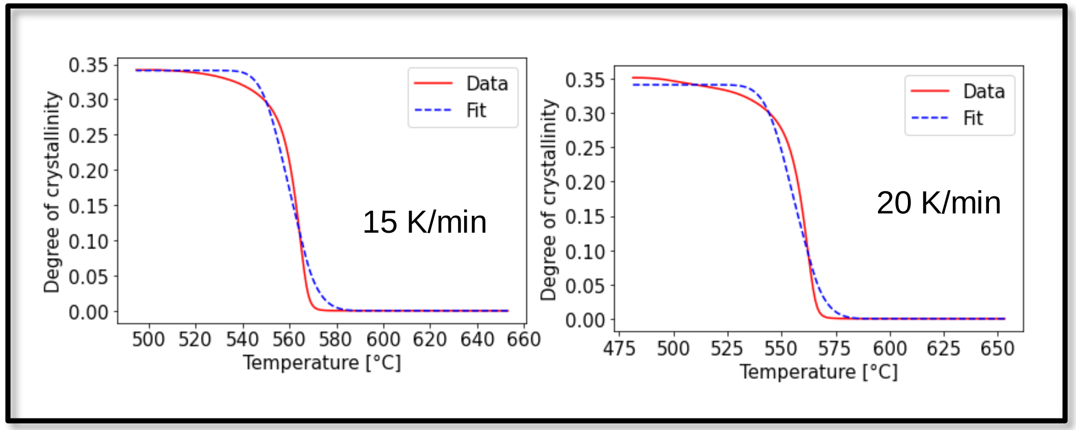
DSC @ different cooling rate

Modelling

Fitting

Analysis





Conclusion and Outlook

- Evaluation of the prediction accuracy:
  - Commercial software vendors provide efficient tools for AM simulations
  - Appropriate representation of the physics
  - Challenge is to apply appropriate boundary conditions, interactions, material models
- „G-Code velocities“ may differ from real velocities -> For precise prediction it is important to have the real printing toolpath
- Real cooling rates are very high (up to 3000K/min) -> Flash DSC measurements probably required to capture crystallization kinetics

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- Validation of deformations and degree of crystallization of a real part

Contact

Thank you for your attention.

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References

- Brenken, B. (2017). *EXTRUSION DEPOSITION ADDITIVE MANUFACTURING OF FIBER REINFORCED SEMI-CRYSTALLINE POLYMERS by School of Aeronautics & Astronautics* (Issue December). PURDUE UNIVERSITY.