Evaluation of the temperature history during extrusion based additive manufacturing

Dr. Robert Hein, Felix Winkelmann, German Aerospace Center
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%

Applied Prusa Printer

Integration of the thermocouple

Cavity + Thermocouple (0.25mm)

Test geometry

Thermocouple (0.25mm)

Printing direction

10 mm

100 mm

25 mm

Measured temperatures
FDM process simulation – Basic concept

CAD

ToolPath Conversation
G-Code->Event-Series

Meshing

Progressive Element Aktivation

Analysis

Thermal boundary conditions
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

<table>
<thead>
<tr>
<th>Velocity [mm/min]</th>
<th>Target [mm/s]</th>
<th>Real [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1000</td>
<td>16.66</td>
<td>16.23</td>
</tr>
<tr>
<td>F2000</td>
<td>33.33</td>
<td>29.91</td>
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<td>F3000</td>
<td>50</td>
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<td>F4000</td>
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<td>F5000</td>
<td>83.3</td>
<td>48.02</td>
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<tr>
<td>F7000</td>
<td>116.67</td>
<td>50.41</td>
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</tbody>
</table>

Acceleration and Deceleration cause delays between predefined and real velocity!
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

\[ X_{vc} = X_{vc\infty}(w_1 F_{\theta_1} + w_2 F_{\theta_2}) \]

\[ F_{\theta_i} = 1 - e^{-\int_0^t k(T)\nu_T^{(n-1)} dt}, i = 1,2 \]

\[ k(T)_i = C_{1i} T e^{-\left(\frac{C_{2i}}{T_c - T + T_{add,i}} + \frac{C_{3i}}{T(T_m,i - T)^2}\right)}, i = 1,2 \]

DSC @ different cooling rate

Fitting

Analysis

Modelling

[Brenken, 2017]
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

• Validation of deformations and degree of crystallization of a real part
Thank you for your attention.

Deutsches Zentrum für Luft und Raumfahrt
German Aerospace Center
Dr.-Ing. Robert Hein
Institute of Composite Structures and Adaptive Systems
Structural mechanics

phone: +49 531 2953237
mail: robert.hein@dlr.de
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