Validation Experiments for LBM Simulations of Electron Beam Melting

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Outline

1 Motivation

2 From Mathematical Model to Numerical Discretization
   - Numerical Model
   - Implementation

3 Validation Experiments for the EBM Process
   - Test Setting
   - Numerical Examples

4 Conclusion & Future Work
EBM Process

1. Preheating of the powder layer
2. Melting of the cross section
3. Lowering of the process platform
4. Application of a new powder layer

(a) Preheating of the powder layer
(b) Melting of the cross section
(c) Lowering of the process platform
(d) Application of a new powder layer
From Mathematical Model to Numerical Discretization

Constitutive Equations

Incompressible Navier-Stokes Equations

\[ \nabla \cdot \mathbf{u} = 0 \]

\[ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \nu \Delta \mathbf{u} + \mathbf{f} \]

Thermodynamic Constitutive Equation

\[ \frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{u}E) = \nabla \cdot (k \nabla E) + \phi \]
Numerical Discretization

**Thermal 3D LBM**

- **Multi-distribution approach** for thermal LBM:

  \[
  f_i(x + e_i, t + \Delta t) = f_i(x, t) + \frac{\Delta t}{\tau_f} \left( f_{i}^{eq}(x, t) - f_i(x, t) \right) + F_i(x, t)
  \]

  \[
  h_i(x + e_i, t + \Delta t) = h_i(x, t) + \frac{\Delta t}{\tau_h} \left( h_{i}^{eq}(x, t) - h_i(x, t) \right) + \Phi_i(x, t)
  \]

  \[
  f_{i}^{eq}(\rho, \mathbf{u}) = \omega_i \rho \left[ 1 + \frac{\mathbf{e}_i \cdot \mathbf{u}}{c_s^2} + \frac{(\mathbf{e}_i \cdot \mathbf{u})^2}{2c_s^2} - \frac{\mathbf{u}^2}{2c_s^4} \right]
  \]

  \[
  h_{i}^{eq}(\rho, \mathbf{u}) = \omega_i E \left[ 1 + \frac{\mathbf{e}_i \cdot \mathbf{u}}{c_s^2} \right]
  \]

- **Macroscopic quantities:**

  \[
  \rho = \sum_i f_i \quad \rho \mathbf{u} = \sum_i \mathbf{e}_i f_i \quad E = \sum_i h_i
  \]
Free Surface Treatment

Volume of Fluid Approach

- Fill level for interface cells is defined by $\varphi$, $0 \leq \varphi \leq 1$
- Simulate only liquid phase and neglect the gas phase
- Reconstruct unknown $f_i, h_i$ values from the gas phase in the interface layer
- Convert interface cells due to the dynamic melt pool surface
Implementation
Summary of Numerical Model

<table>
<thead>
<tr>
<th>Model includes</th>
<th>Unfortunately missing</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Parallelized and optimized 3D thermal LBM</td>
<td>• Temperature dependent surface tension :(</td>
</tr>
<tr>
<td>• Wetting effects</td>
<td>• Evaporation model :(</td>
</tr>
<tr>
<td>• Free surface treatment</td>
<td>• ... ;(</td>
</tr>
<tr>
<td>• Different absorption types (constant, exponential)</td>
<td></td>
</tr>
<tr>
<td>• Realistic metal powder distribution (TiAl6V4)</td>
<td></td>
</tr>
</tbody>
</table>
Experiment Setting for Validation

• **Line energy**

\[
E_L = \frac{u_B I_{\text{beam}}}{v_{\text{scan}}} = \frac{P_{\text{beam}}}{v_{\text{scan}}} \left[ \frac{\text{kJ}}{\text{m}} \right]
\]

with

• acceleration voltage \( u_B \) in V
• beam current \( I_{\text{beam}} \) in A
• scan velocity \( v_{\text{scan}} \) is scan velocity in \( \frac{\text{m}}{\text{s}} \)

• Examination of a sample regarding
  • porosity
  • bulges
  • behavior of melt pool

• **Hatching of a cuboid considering**
  • different \( v_{\text{scan}} \)
  • different \( E_L \)

[Diagram of a cuboid with dimensions 15mm x 15mm x 10mm]
Categorization of Test Settings

Porosity  
Good Surface  
Bulges

Line Energy
Process Window of the 1.2kW Gun
Hatch – porous

6.4 \text{ m/s}, 100 \text{ kJ/m}
Hatch – non-porous

$6.4 \frac{m}{s}, 200 \frac{kJ}{m}$
Validation Results

Porosity for different line energies with 6400mm/s
Validation Results

Max Temperature for different line energies with 6400mm/s
Validation Results

Melt Pool Volume for different line energies with 6400mm/s
More Powder Layers!

$6.4 \frac{m}{s}, 200 \frac{kJ}{m}$
Outlook

Conclusion
• 3D numerical model for the EBM process
• Validation examples show the appropriate behavior of EB – powder bed interaction for the given process window

Future Research
• Find the best parameter set $(E_L, v_{\text{scan}})$ for a faster and higher quality EBM process
• Examine the behavior of more layers and their interaction
• Include temperature dependent surface tension!
• Examine different evaporation models and include!
• . . . never ending story . . .
Not physical, but nice...
Acknowledgments & References

EU Grand Agreement Number 28 66 95 – FastEBM
High Productivity Electron Beam Melting Additive Manufacturing Development for the Part Production Systems Market

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