Additive Manufacturing

From Trial and Error to a Standard Industrial Process
Topics

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• Introduction
• Process Simulation of AM
  – Metals
  – Polymers and Composites
• Conclusion
Additive Manufacturing (AM) opens up amazing possibilities
It also comes with its own, unique challenges

- Optimized Shape
- Reduced Try-Out
- First Time Right
- Shorter Print Time
- Optimal Support Structure
- Minimize material Usage
- Efficient Serial Production
- Correct Microstructure
- Porosity
- Part Performance

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Main challenges

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• Distortion
  – Part out of tolerances
  – Collision with powder scraper

• Residual Stresses
  – Part of support failure

• Quality
  – Porosity
  – Microstructure
Additive Manufacturing (AM) Process

Design  Build  Inspect
With manufacturing simulation
AM Process Simulation
Analysis scales

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- Moving heat source
- Transient fully thermo-mechanically metallurgical coupled
- Delivers thermal history and derived results like microstructure

- Element layer (> powder layer) analyzed in one step
- Inherent Strains - pure mechanically, extremely fast
- Delivers Distortion & Stress

- Element layer analyzed in one step or by hatching segments
- Thermal, mechanical or thermo-mechanically coupled
- Able to deliver approximate thermal history and derived

micro scale  meso scale  macro scale
Macro scale

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**Implementation**
- Voxel technique
- Inherent strain
- Layer based

**Results**
- Part distortion
- Residual stress

**Benefit**
- Extremely fast
- Simple calibration

CPU Time
5 minutes
Voxel technique with solid fraction
Inherent strain

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Comprise
- Plastic strains
- Thermal strains
- Creep strains
- Phase transformation strains

Reflect
- Material
- Manufacturing parameters
- (Individual) machine

Are orthotropic by nature
Calibration of inherent strain by simple cantilever build

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Step 1: Build cantilevers ➔ Cut ➔ Measure tip displacement
Step 2: Automatic calibration

Store in database
Once calibrated, run simulations on actual parts
Validation Examples
Validation example
Validation example
Validation example
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**Validation example**

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**Distortions**

<table>
<thead>
<tr>
<th>Point</th>
<th>Simulation (mm)</th>
<th>Experiment (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3539</td>
<td>0.3532</td>
</tr>
<tr>
<td>2</td>
<td>0.5527</td>
<td>0.5517</td>
</tr>
<tr>
<td>3</td>
<td>0.5931</td>
<td>0.5920</td>
</tr>
</tbody>
</table>

**Cross Section Contour Distortion**

- **Simulation**
- **Experiment**

Scaled displacement = 10x
Validation example

Parameter Set 1

Sinterline® powder (Glass beads reinforced polyamide)

Experiment

Simulation
Validation example

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Stratasys – Composite Tooling

Warpage prediction after geometry compensation in Digimat-AM.
Left: superposition of the as-printed (red) and as-design (green) parts.
Right: RMS signed distance. Maximum deviation is below 0.1 mm.
Virtually explore the influence of:

- Manufacturing parameters & materials
- Cutting direction & supports removal sequence
Virtually explore the influence of:

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- Build orientation

- Support structure configuration
Virtually explore the influence of:

- Process chain

- AM Build
- Heat Treatment
- Cut from Plate
- Cooling
- Remove Supports
- HIP
Virtually explore the influence of:

- Optimal compensated shape
Polymers Example
Consideration of polymer parts

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Additive Layer Manufacturing

- FFF/SLS
  - Process Simulation
    - Part Performance
      - Material Engineering
        - Mechanical
        - Thermal
        - Electric
        - Warpage
        - Residual Stress
        - Porosity
        - Stiffness
        - Failure
      - Print Direction
      - Reinforcement
      - Reinforcement
      - Reinforcement
Sinterline® plenum chamber; Powder Bed Fusion (SLS)

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• Plenum is part of the Polimotor project (all plastics engine)
• Long-term goals:
  • Introducing plastic parts in future automotive engines
  • Highlighting trailblazing polymer technologies and their potential
• Challenge: the additively manufactured plenum must demonstrated that:
  • It can withstand the working loads
  • It can perform with same reliability as its injection molded counterpart
Material characterization with nonlinear micro-mechanics

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Input

Homogenization

Output

Mean Field

Finite Element

\[
\Delta\varepsilon_r = \langle \Delta\varepsilon(x) \rangle_r = H_r : \Delta E
\]

Global behavior

Localization

\[
\Delta\sigma_r = c_r : \Delta\varepsilon_r
\]

Local phase behavior

Averaging

\[
\Delta\sigma = \tilde{c}(c_r) : \Delta\varepsilon
\]

Stress

Strain

Fiber orientation

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Sinterline® material characterization

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Stress-Strain curves and Failure dependent on printing orientation

**Tensile test (RH0), depending of printing orientation, compare to Digimat model**

- True Stress (MPa) vs. True Strain (%)
- Samples printed at: 0°, 15°, 30°, 45°, 60°, 75°, 90°
- Failure points

**Compressive tests (RH0) depending on samples printing orientation, compare to Digimat model**

- True Stress (MPa) vs. True Strain (%)
- Experimental vs. Digimat model
- Samples printed at: 0°, 15°, 30°, 45°, 60°, 75°, 90°
Simulate AM build process
Performance analysis

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Pressure at failure for different build orientations

• Build in width direction 12.8 bars
• Build in height direction 12.0 bars
• Build in length direction 8.1 bars
• Build in angled orientation 9.1 bars
Experimental testing

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• Method
  • Pressure increase by steps up to 6 bars positive air pressure inside the plenum
  • Pressure release to ambient pressure after 1 hour at 100 degrees C

• Conclusion
  • No burst of the part during test validation of part strength
  • Test successful

![Experimental pressure profile](image1)
![Experimental set up](image2)
Metal AM Simulation - Prediction of microstructure

Transient simulation with microstructure in cooperation with MRL

- AM- LPBF
  - Ti6Al4V
  - CoCr
  - 316L
  - IN625
  - IN718

- SEM EBSD
  - 100 Million orientations
  - >10,000 Images

- 7 °C/min
  - 1500°C/min
  - High-Throughput HT & mechanical testing

- AM Processing and Performance FE simulations

- AM ICME platform for data analytics, material modeling, and FEM simulations
Conclusion

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- You can design amazing structures – simulation is a must to reliably print them

- Simulation is required for:
  - the whole process (build, cut, heat-treat),
  - the complete chain (material, process, performance)
  - At different scales (macro, meso, micro)

- New simulation tools are available and are advancing rapidly