Modeling and Calibration of Additive Manufacturing Processes using the Example of the Additive Layer Manufacturing Process (ALM)

Dieter Hummel*1, Waldemar Schwarz*1
Jiri Drozda*2, Roger Schlegel*2

*1 ArianeGroup GmbH, München
*2 Dynardo GmbH, Weimar

15th Weimar Optimization and Stochastic Days
June 21-22, 2018
Why parametrized simulation for Additive Manufacturing?

challenges in AM process

- thermal history, overheating
- distortion of the printed structures
- residual stresses during the AM process
- structural damage, defects & cracks because of the AM process

parametrized simulation can help:

- to find the necessary discretization niveau of a simulation model and to calibrate the simulation model for sufficient prognosis quality
- to find relevant, sensitive process parameter to ensure necessary product quality (especially for dimensioning-relevant components)
- to reduce the costly Trial & Error process
ALM – ANSYS optiSLang workflow

Process parameter

✓ Laser power
✓ Melt velocity
✓ Melt temperature
✓ Melt zone size
  • diameter
  • depth
  • Overlap
✓ Laser - Direction ±67°
✓ Cooling time of melt pot
  • $t_{cool}$ time before the next layer is melted
  • $t_{wait}$ time to the next powder placement

\[
\text{vol}_{\text{weld}} = v_{\text{weld}} \cdot (d_{\text{weld}} - u_{\text{weld}}) \cdot t_{\text{weld}} = 10.80 \text{ mm}^3/\text{sec}
\]

15th Weimar Optimization and Stochastic Days
June 21-22, 2018

by courtesy of arianeGROUP
ALM – ANSYS optiSLang workflow

Thermal Simulation
(temperature fields)

Mechanical Simulation
(stress, strain, deformation)
ALM - ANSYS optiSLang workflow

Using Kill & Alive Option from ANSYS mechanical

Geometry (Volumes) via set of layers (volumes) Sliced (boolean operation)

Geometry (slices and base plate) Meshed freely (elements must not cross inactive via Kill-command joint faces between slices) Construction element set
ALM – ANSYS optiSLang workflow
Kill & Alive Option from ANSYS mechanical

Transient Thermal-Analysis
• „ALIVE – Element volumes are heated to melt temperature
• Calculate Temperature distribution until the next set of elements will „alive“

Non-linear Structural-Analysis
• Elasto-plastic material modeling
• „Alive“ elements are initialized with approximated Temperatures
• Per step stresses and strains (elastic+plastic) are calculated
How fine the mesh needs to be?
Convergence studies on the test structure show reasonable convergence with 3 to 4 elements over one layer (1.8 mm) resulting in element size of the Quader 0.6 mm.
ALM – ANSYS optiSLang Workflow

optiSLang parameter sensitivity analysis

possible combinations of the discretization of the ALM Layer

lauf_br = 10 mm
lauf_br = 3,5 mm
lauf_rot = 0°

lauf_br = 20 mm
lauf_br = 0,9 mm
lauf_rot = 0°
The higher the resolution of the process zone, the more continuous the energy input and the smaller the deformation.
AM – ANSYS optiSLang workflow

Parametric modeling for material, mesh, slicing & AM process

optiSLang®

Calibrated Simulation

ANSYS: Thermal and Mechanical Simulation

Calibration

Sensitivity Study and Metamodelling
ALM - ANSYS optiSLang workflow

optiSLang parameter sensitivity analysis

• 150 Latin hypercube samplings

<table>
<thead>
<tr>
<th>Name</th>
<th>Parameter type</th>
<th>Reference value</th>
<th>Constant</th>
<th>Value type</th>
<th>Resolution</th>
<th>Range</th>
<th>Range plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>lauf_brx</td>
<td>Optimization</td>
<td>5</td>
<td></td>
<td>REAL</td>
<td>Ordinal discrete (by index)</td>
<td>10; 20; 40; 80</td>
<td></td>
</tr>
<tr>
<td>lauf_bry</td>
<td>Optimization</td>
<td>3.6</td>
<td></td>
<td>REAL</td>
<td>Ordinal discrete (by index)</td>
<td>0.9; 1.8; 3.6; 7.2</td>
<td></td>
</tr>
<tr>
<td>lauf_rot</td>
<td>Optimization</td>
<td>0</td>
<td></td>
<td>REAL</td>
<td>Continuous</td>
<td>0; 67</td>
<td></td>
</tr>
<tr>
<td>del_t</td>
<td>Optimization</td>
<td>1</td>
<td></td>
<td>REAL</td>
<td>Continuous</td>
<td>0.9; 1.1</td>
<td></td>
</tr>
<tr>
<td>alf</td>
<td>Optimization</td>
<td>0.05</td>
<td></td>
<td>REAL</td>
<td>Continuous</td>
<td>0; 1</td>
<td></td>
</tr>
</tbody>
</table>
ALM – ANSYS optiSLang workflow

Metamodeling after Sensitivity Analysis

- **CoP Matrix (Coefficient of Prognoses)**

Influences (%) of process input parameters

Regarding the exposed volumes and the deformation

Meta-model shows range of variation and trends of maximum deformation

Metamodel of Optimal Prognosis (MOP)
Material properties, anisotropy

material printed in layers

anisotropic material behavior

homogeneous, anisotropic, multi-surface material model

Yield surfaces of the anisotropic layer printed material model
ALM - ANSYS multiPlas
Anisotropic material modeling

Material Data Anisotropy

- Measured mean values X, Y and Z
  n – normal to layer, in printing direction
  p – parallel to layer

- $E_n \approx 0.87 \ E_p$
- $R_{p0.2\_n} \approx 0.80 \ R_{p0.2\_p}$
- $R_{m\_n} \approx 0.88 \ R_{m\_p}$
- $A_n \approx 1.24 \ A_m$

- Temperature dependent

- First realization uses available anisotropic box-value model in multiPlas

Stress-Strain curves (300 K)

- isotropic (first assumption)
- 1. Measurement, n-direction
- 2. Measurement, n-direction
- 1. Computation, n-direction
- 2. Computation, p-direction
- 1. Computation, p-direction
ALM - ANSYS optiSLang workflow

Material parameter

Re-cristalization

- At cooling process of melt temperature from 1700 K to 1100 K no relaxation of plastic strain and stress
- Heat expansion coefficient varies between 1700K and 1000K
- Parameter alf between 0 und 1
ALM – ANSYS optiSLang Workflow

Metamodelling after Sensitivity Analysis

- CoP Matrix (Coefficient of Prognoses)

Influences (%) of process input parameters regarding the stresses on different locations MS1 – MS3’
Optimization – objective function for calibration

\[
\text{Obj} = \text{Obj}_\text{Uz} + \text{Obj}_\text{MS}_\text{Sx} + \text{Obj}_\text{MS}_\text{Sy} + \text{Obj}_\text{MS}_\text{Sz} + \text{Obj}_\text{MS} '_\text{Sx} + \text{Obj}_\text{MS} '_\text{Sy} + \text{Obj}_\text{MS} '_\text{Sz} \quad [\%]
\]

Optimization process → best fit for distortion and stress

**MOP Solver**

Reduction of calculation time

MOP-process 2300 designs → 1 h
ALM – ANSYS optiSLang Workflow

Parameter Calibration using metamodeling
• Very good agreement was achieved
• Residual stress are within the window of variation from measurements

Check of the best design with real solver run was successfully.

Calibrated Parameter set:
lauf_brx = 20 mm
lauf_bry = 0.9 mm
lauf_rot = 66.75°
alf = 0.7682
Summary

ALM - ANSYS optiSLang workflow: available features

- parametrized simulation workflow for additive manufacturing
- geometry slicing & free-meshing for arbitrary geometries
- Kill & Alive Option from ANSYS mechanical
- Thermal – Mechanical simulation for
  - thermal process optimization
  - deformation, stress, crack prognosis with special nonlinear material model
- Includes stress relocation after cutting off parts from supports (kill contact elements)
- all optiSLang functionality for model calibration, sensitivity analysis, product / process optimization, robustness evaluation