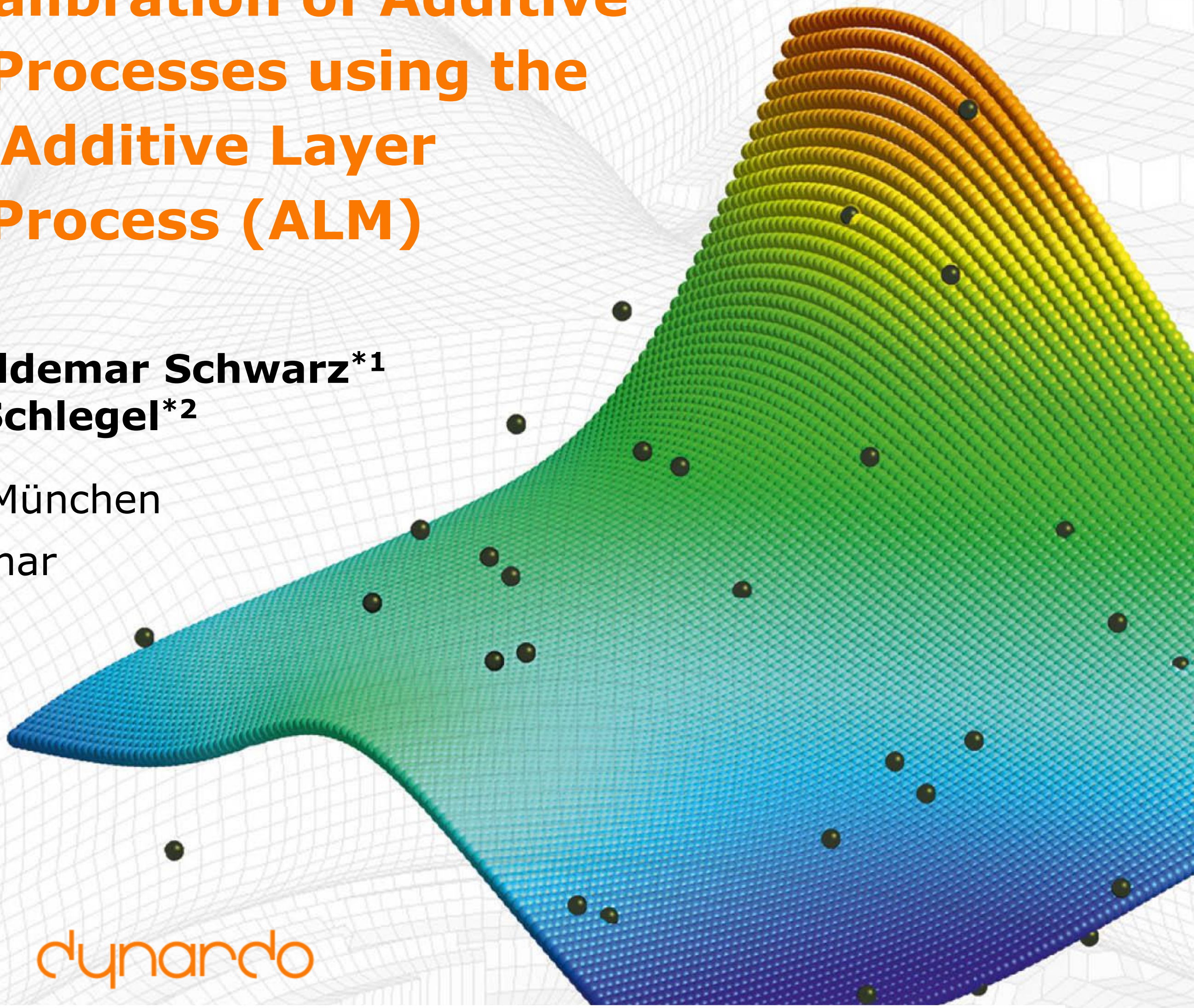
dynardo

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



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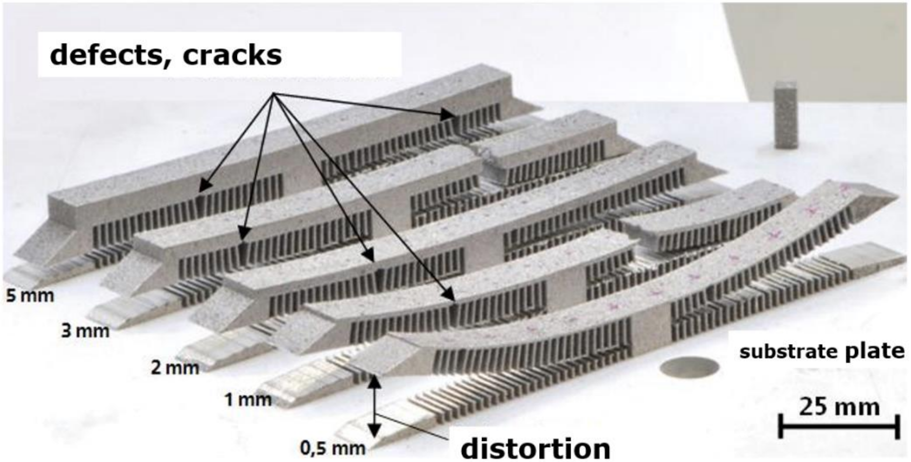
15th Weimar Optimization and Stochastic Days
June 21-22, 2018

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



Source: BUCHBINDER et. al, RTejournal 2010

parametrized simulation can help:

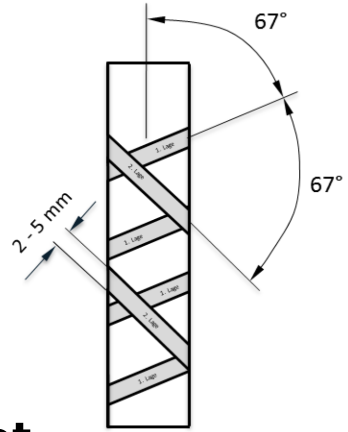
- to find the necessary discretization niveau of a simulation model and to calibrate the simulation model for sufficient prognosis quality
- to find relevant, sensitive process parameter to ensure necessary product quality (especially for dimensioning-relevant components)
- to reduce the costly Trial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

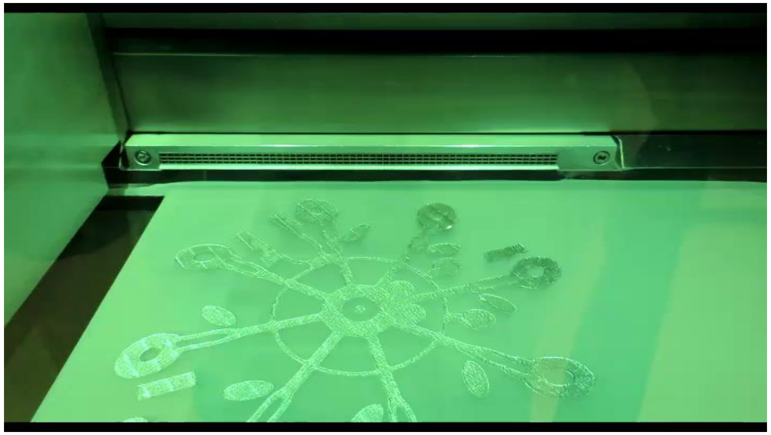
by courtesy of arianeGROUP

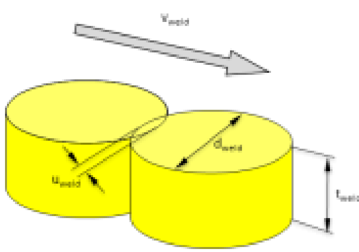
ALM – ANSYS optiSLang workflow

Process parameter

- ✓ **Laser power**
- ✓ **Melt velocity**
- ✓ **Melt temperature**
- ✓ **Melt zone size**
- • diameter
- • depth
- • Overlap
- ✓ **Laser - Direction ±67°**
- ✓ **Cooling time of melt pot**
- • tcool time before the next layer is melted
- • twait time to the next powder placement







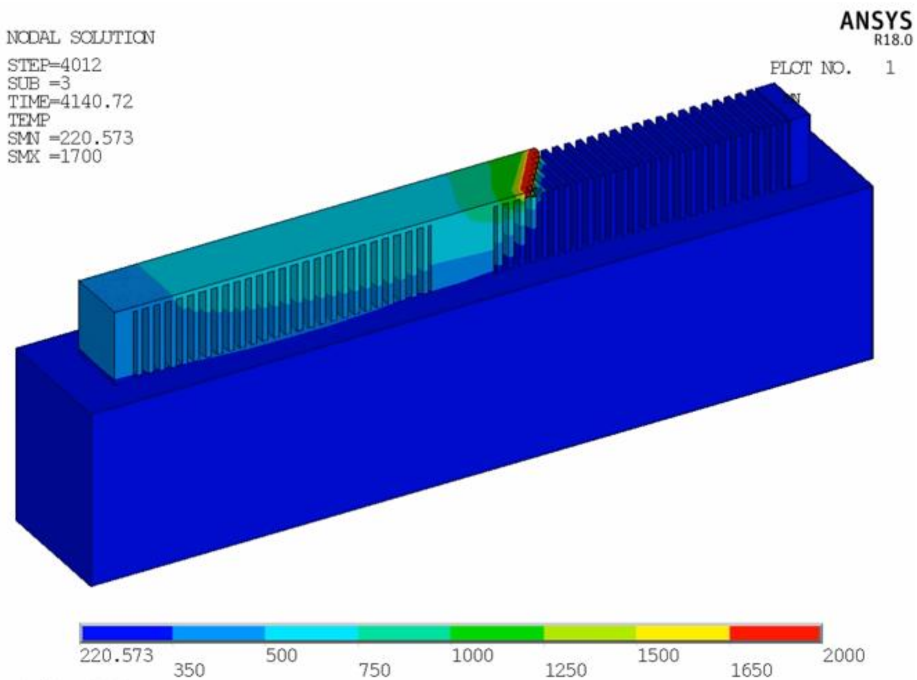
• v_{weld} =	Laser speed	1200	mm/sec
• d_{weld} =	Laser diameter	0.1	mm
• t_{weld} =	Laser depth	0.1	mm
• u_{weld} =	Overlap	0.01	mm

$$vol_{weld} = v_{weld} \cdot (d_{weld} - u_{weld}) \cdot t_{weld} = 10.80 \left[\frac{mm^3}{sec}\right]$$

ALM – ANSYS optiSLang workflow

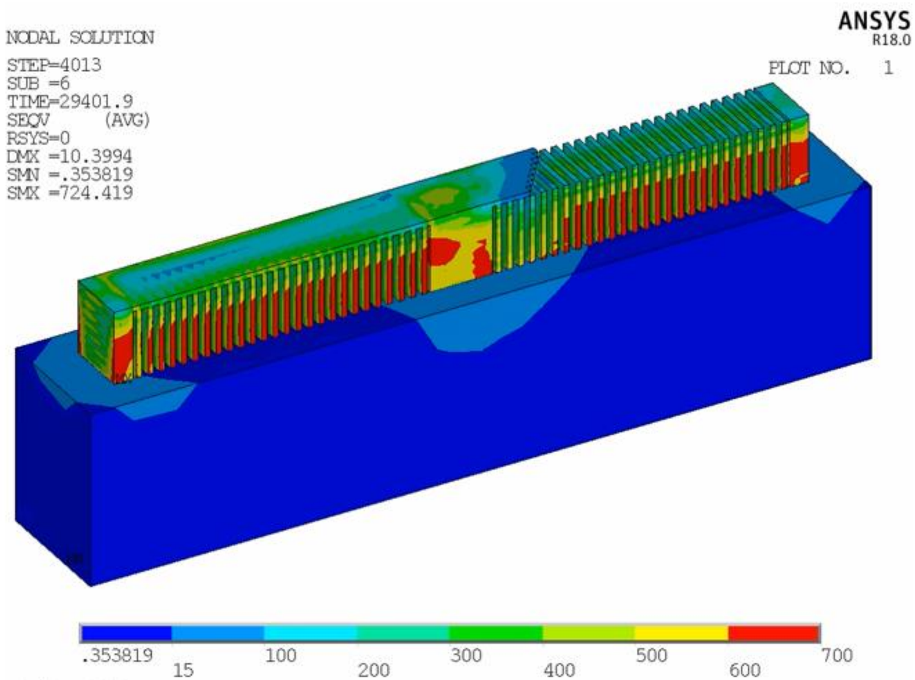
Thermal Simulation

(temperature fields)



Mechanical Simulation

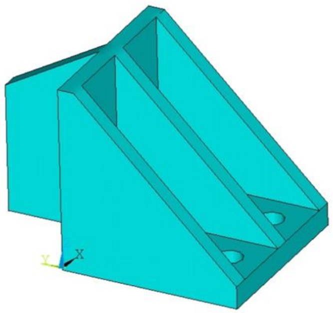
(stress, strain, deformation)



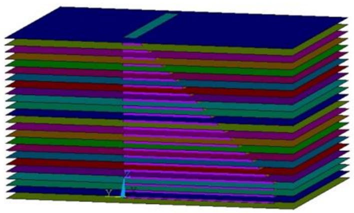
by courtesy of arianeGroup

ALM - ANSYS optiSLang workflow

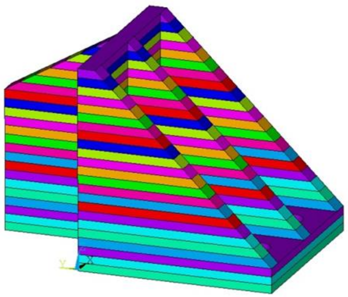
Using Kill & Alive Option from ANSYS mechnical



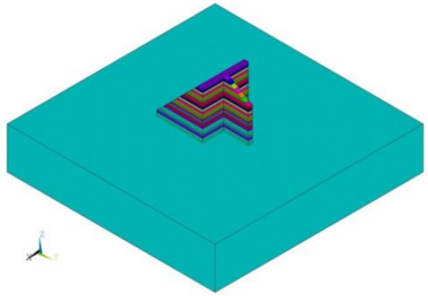
Geometry (Volumes)



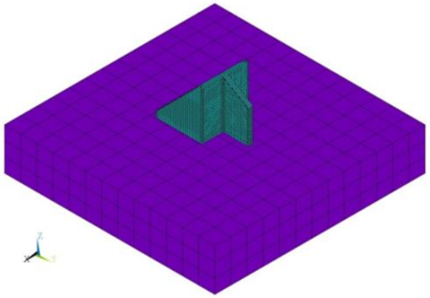
via set of layers (volumes)



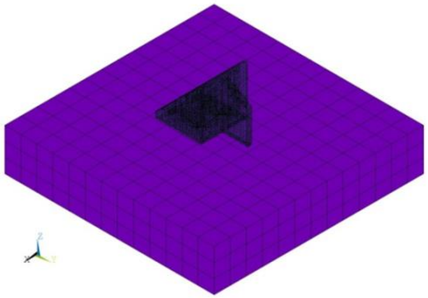
Sliced (boolean operation)



Geometry
(slices and base plate)



Meshed freely
(elements must not cross joint faces between slices



Construction element set inactive via Kill-command

by courtesy of arianeGROUP

ALM – ANSYS optiSLang workflow

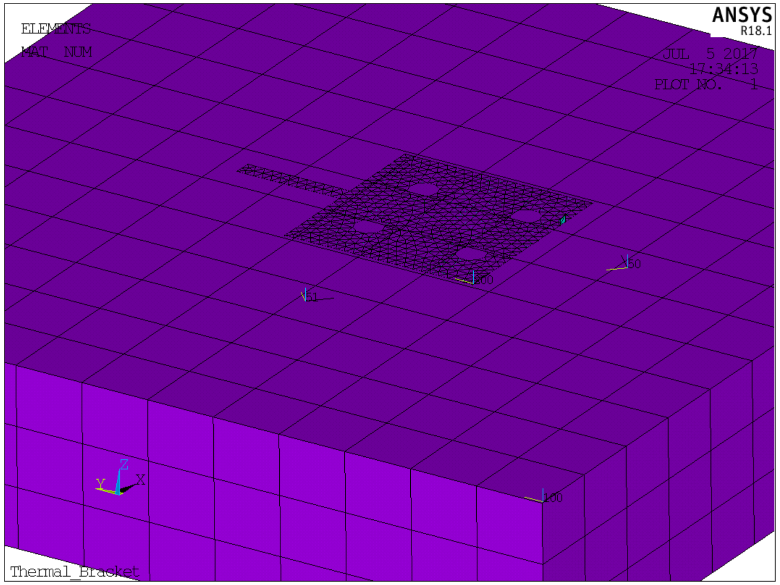
Kill & Alive Option from ANSYS mechanical

Transient Thermal-Analysis

- „ALIVE – Element volumes are heated to melt temperature
- Calculate Temperature distribution until thenext 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



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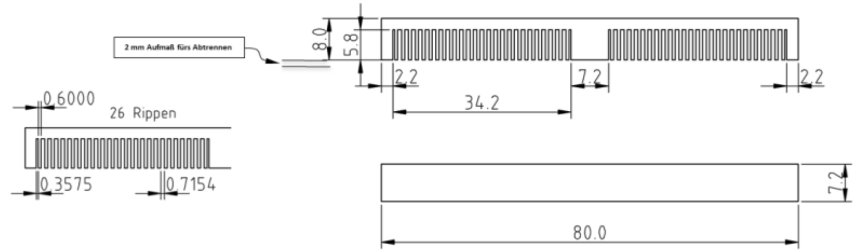
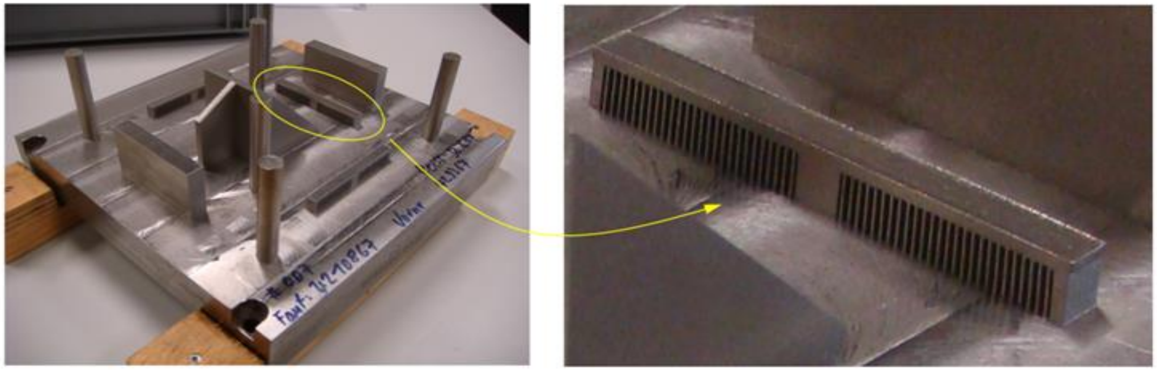
ALM - ANSYS optiSLang workflow

Reference Specimen





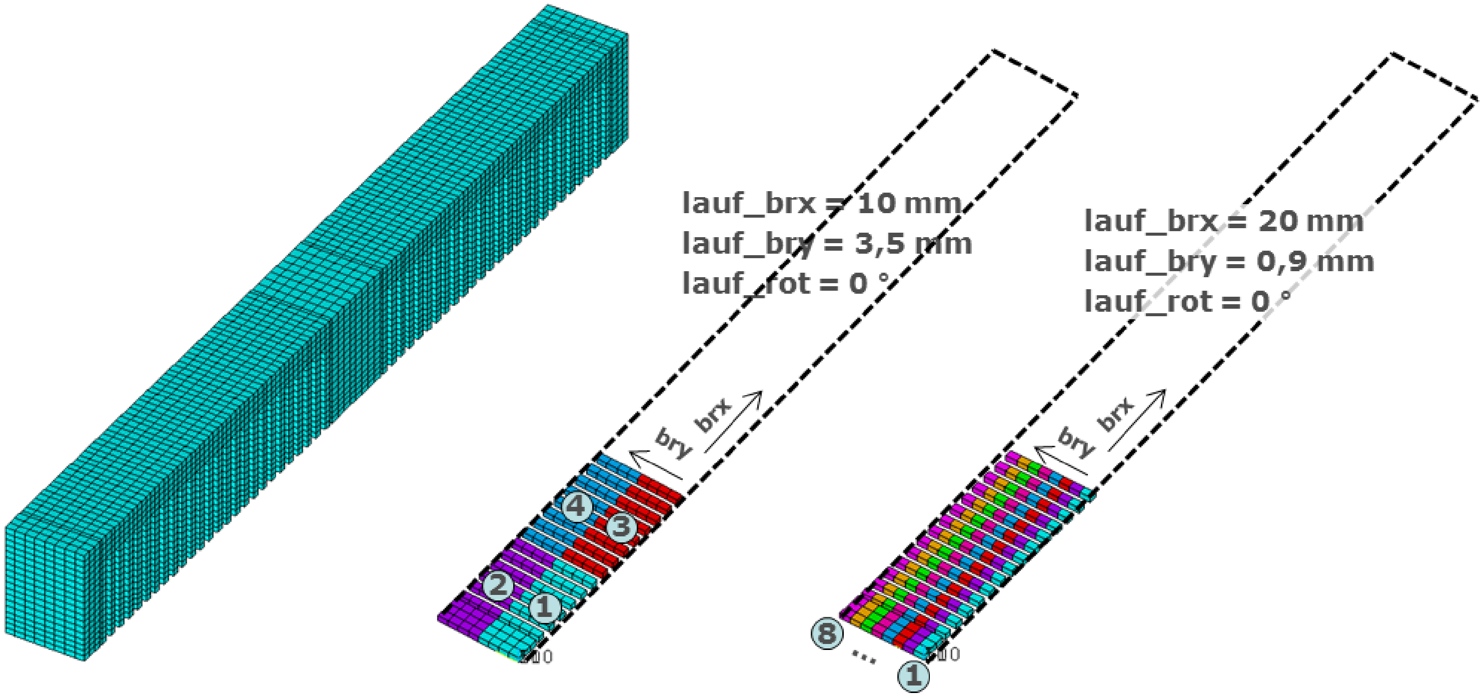
How fine the mesh needs to be?

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.

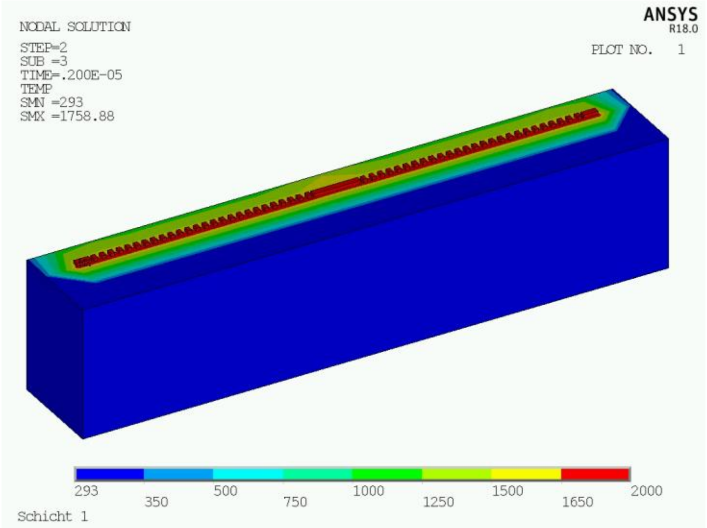
ALM – ANSYS optiSLang Workflow

optiSLang parameter sensitivity analysis

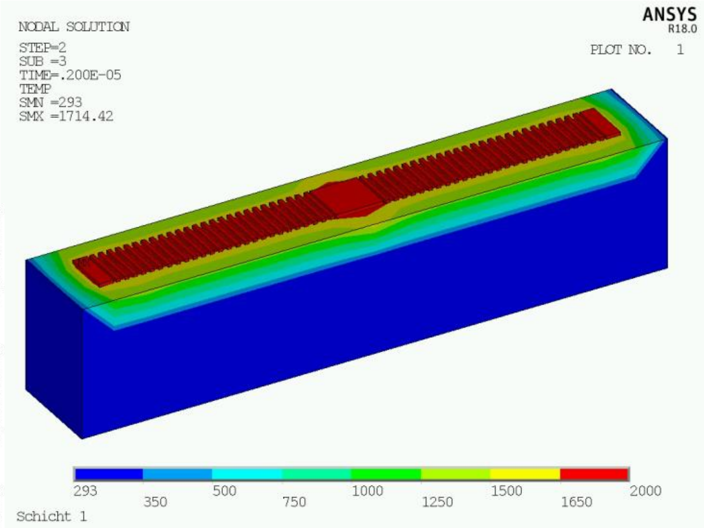
possible combinations of the discretization of the ALM Layer

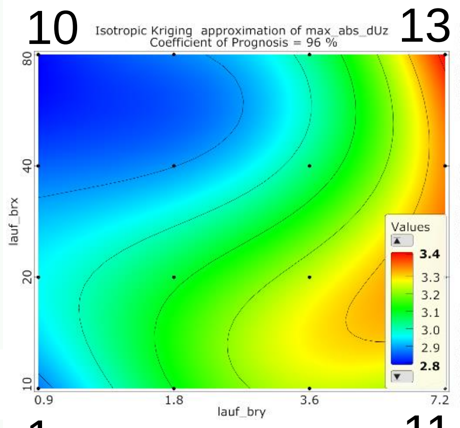


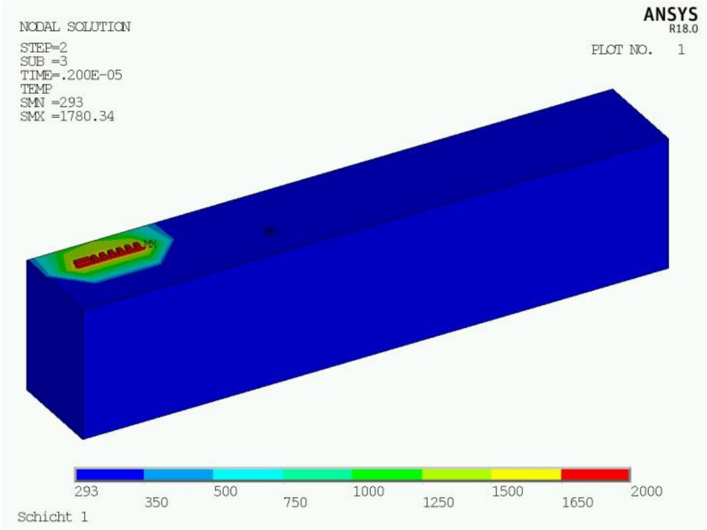
by courtesy of arianeGROUP

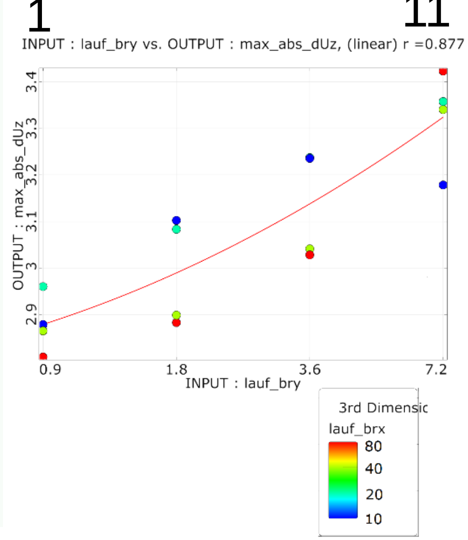


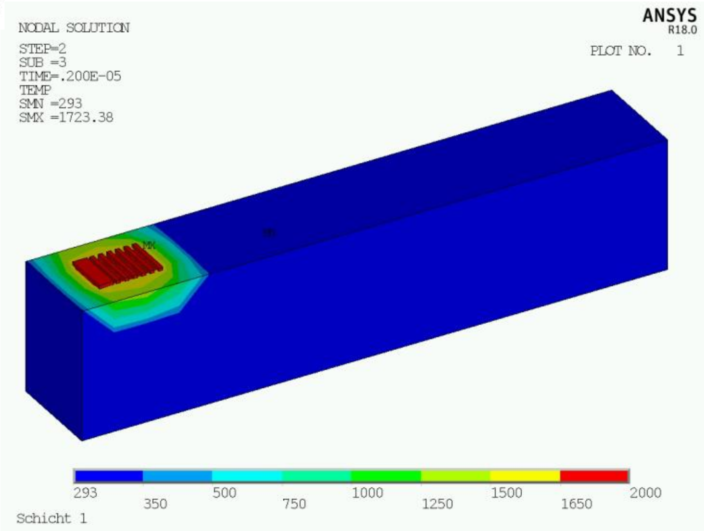
The higher the resolution of the process zone, the more continuous the energy input and the smaller the deformation.





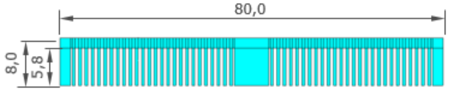




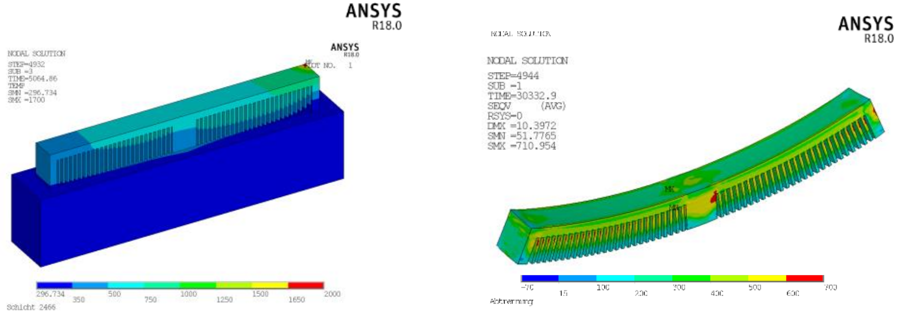


AM – ANSYS optiSLang workflow

Parametric modeling for material, mesh, slicing & AM process

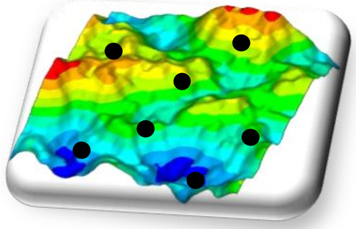


ANSYS: Thermal and Mechanical Simulation

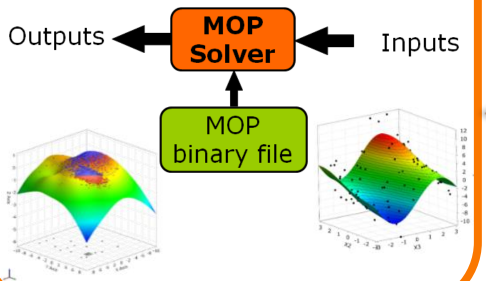


optiSLang

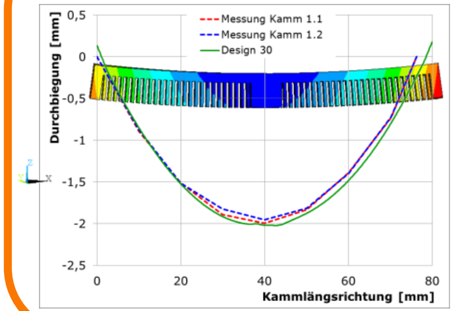
Sensitivity Study and Metamodeling



Calibration



Calibrated Simulation



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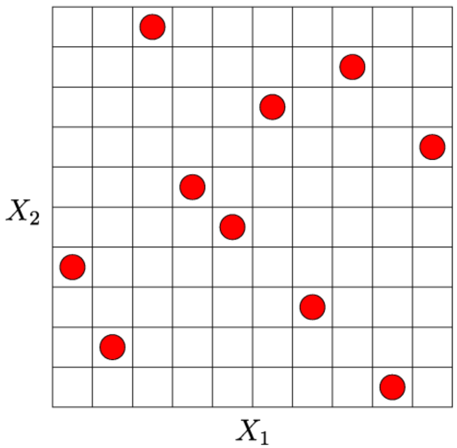
ALM - ANSYS optiSLang workflow

optiSLang parameter sensitivity analysis

- 150 Latin hypercube samplings

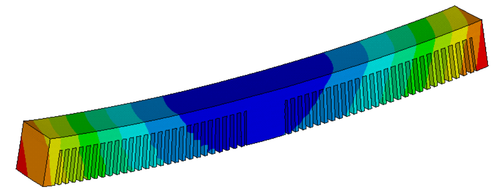


	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range		Range plot
1	lauf_brx	Optimization	5	☐	REAL	Ordinal discrete (by index)	10; 20; 40; 80		
2	lauf_bry	Optimization	3.6	☐	REAL	Ordinal discrete (by index)	0.9; 1.8; 3.6; 7.2		
3	lauf_rot	Optimization	0	☐	REAL	Continuous	0	67	
4	del_t	Optimization	1	☑	REAL	Continuous	0.9	1.1	
5	alf	Optimization	0.05	☐	REAL	Continuous	0	1	

ALM – ANSYS optiSLang workflow

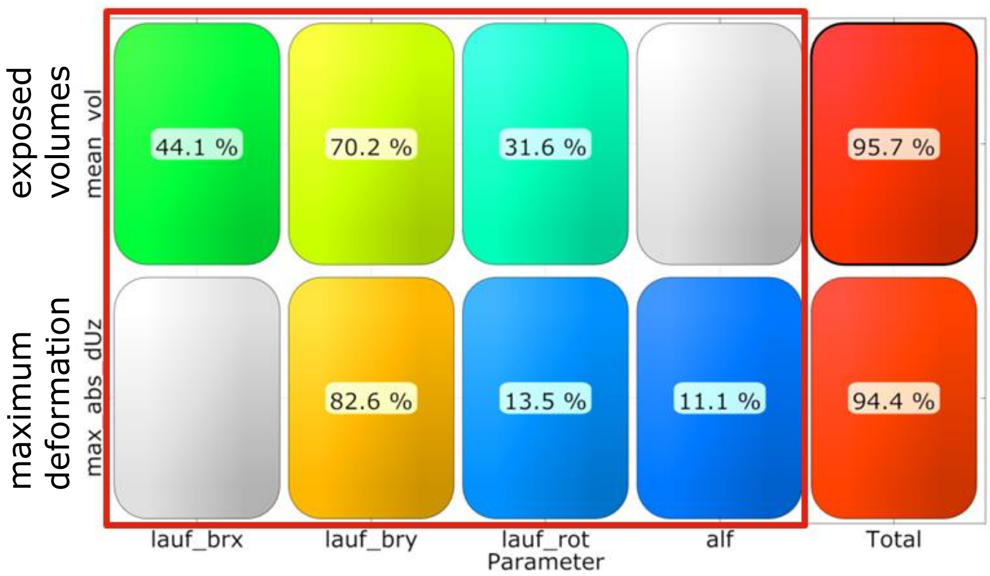
Metamodeling after Sensitivity Analysis

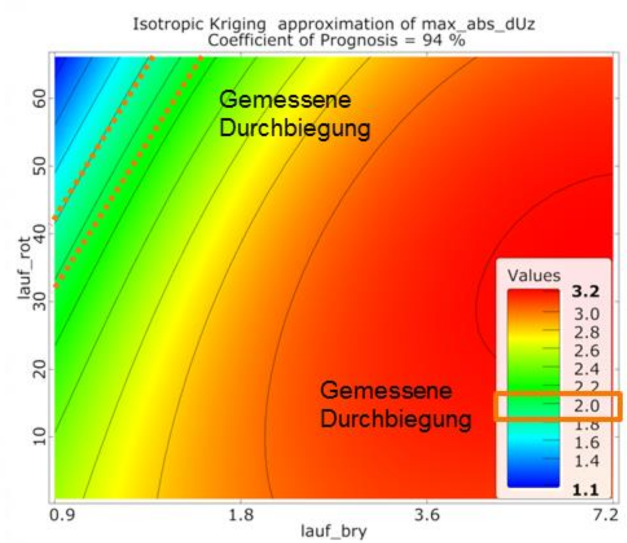
- **CoP** Matrix (**C**oefficient **o**f **P**rognoses)



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)

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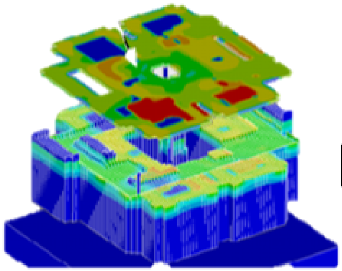
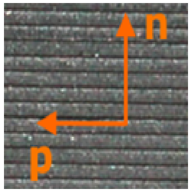
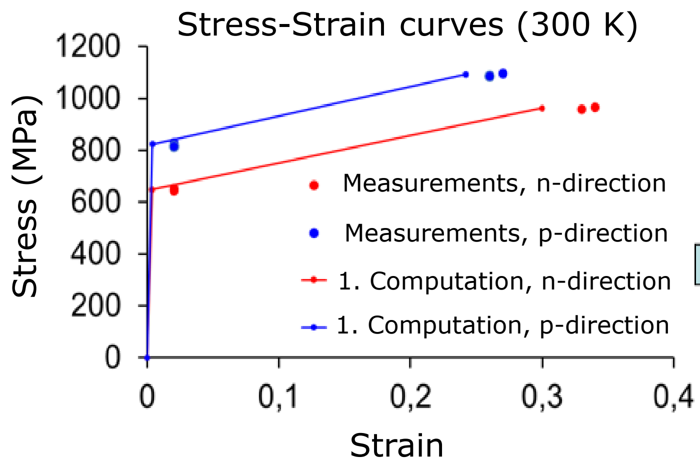
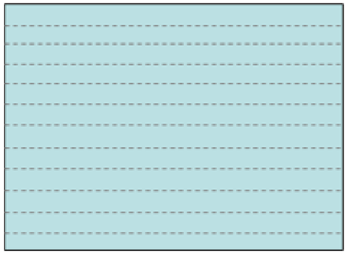
Material properties, anisotropy









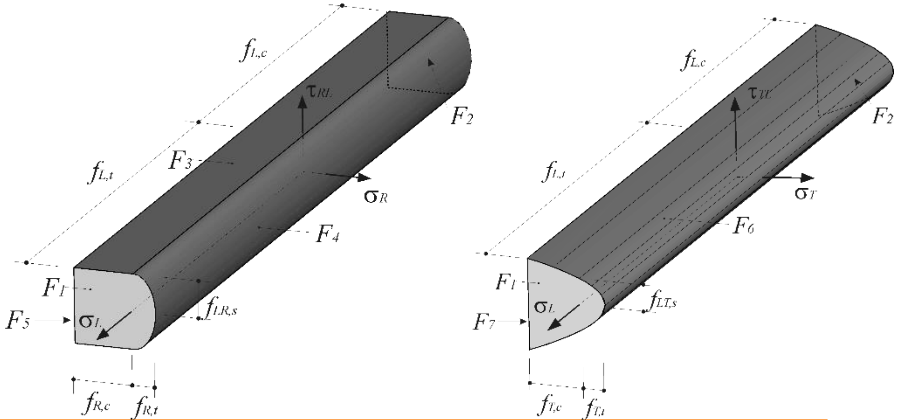
material printed in layers

anisotropic material behavior

homogeneous, anisotropic, multi-surface material model

multiPlas

Yield surfaces of the anisotropic layer printed material model

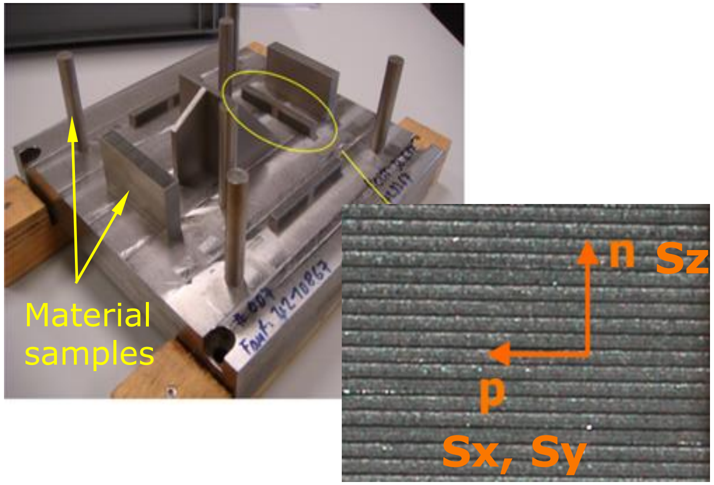


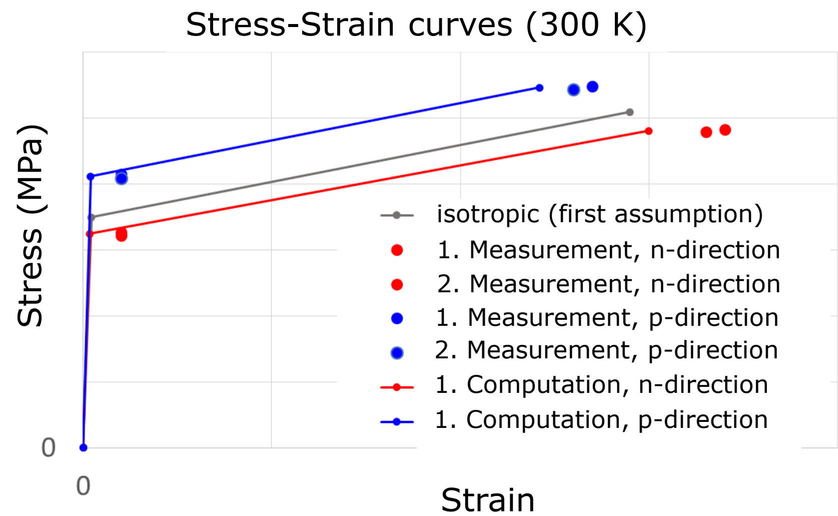
ALM - ANSYS multiPlas

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



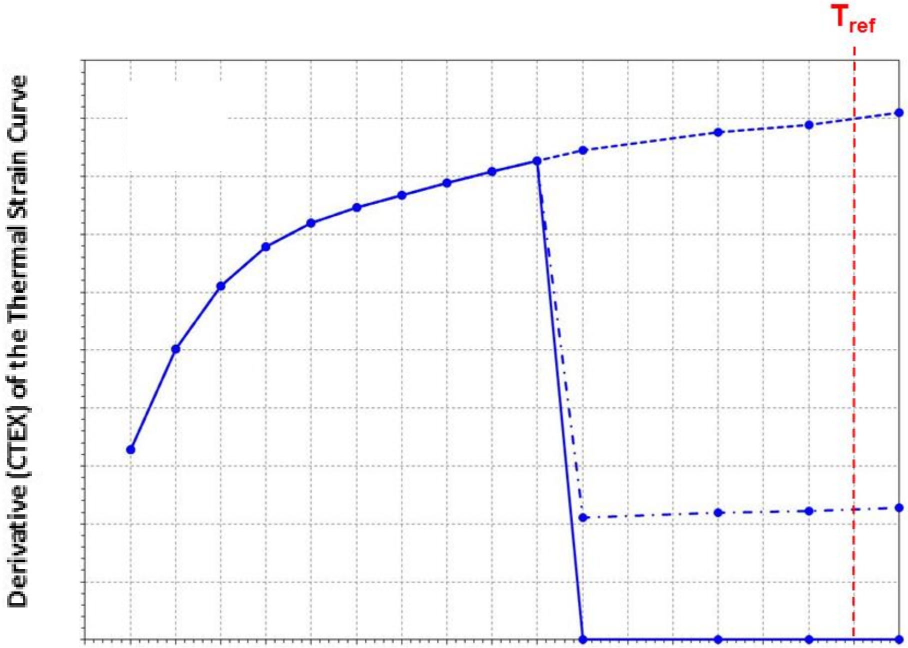


ALM - ANSYS optiSLang workflow

Material parameter

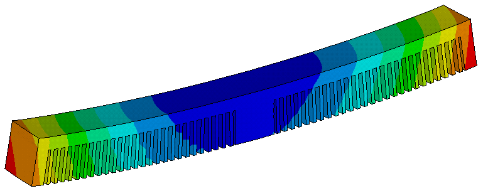
Re-cristalization

- 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



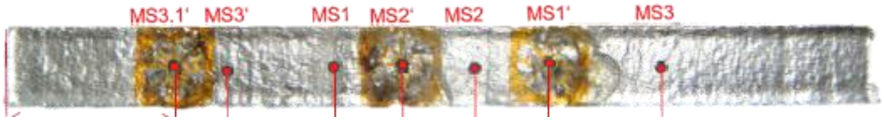
temperature

ALM – ANSYS optiSLang Workflow



Metamodeling after Sensitivity Analysis

- **CoP** Matrix (**C**oefficient **o**f **P**rognoses)



Influences (%) of process input parameters regarding the stresses on different locations MS1 – MS3'

vor Erodieren

Models	lauf_brx	lauf_bry	lauf_rot	alf	Total
MS3_Sy_0_K		65.9 %	7.8 %	17.8 %	87.0 %
MS3_Sy_0.6_K		50.0 %	13.4 %	12.9 %	75.6 %
MS3_Sx_0_K		64.1 %	21.7 %	14.6 %	79.9 %
MS3_Sx_0.6_K		52.5 %	20.3 %	15.0 %	83.6 %
MS2_Sy_0_K	6.7 %	75.7 %	8.4 %	14.4 %	95.6 %
MS2_Sy_0.6_K		71.7 %	13.1 %	9.0 %	90.3 %
MS2_Sx_0_K		77.7 %	32.2 %	19.1 %	90.0 %
MS2_Sx_0.6_K		52.1 %	42.9 %	19.0 %	80.5 %
MS1_Sy_0_K		77.8 %	6.6 %	13.1 %	93.7 %
MS1_Sy_0.6_K	3.3 %	56.3 %	3.0 %	8.9 %	72.6 %
MS1_Sx_0_K		65.8 %		23.5 %	74.9 %
MS1_Sx_0.6_K		43.2 %		19.8 %	60.5 %

Parameter

nach Erodieren

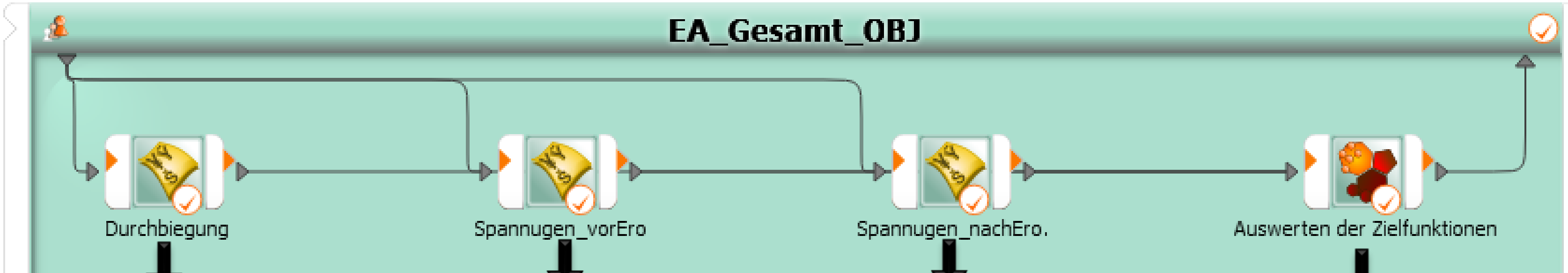
Models	lauf_brx	lauf_bry	lauf_rot	alf	Total
MS3'_Sy_0_K		66.5 %	8.3 %	9.7 %	84.0 %
MS3'_Sy_0.6_K		52.3 %	23.6 %	6.5 %	85.8 %
MS3'_Sx_0_K		56.7 %	25.0 %		76.4 %
MS3'_Sx_0.6_K		33.9 %		9.6 %	43.8 %
MS2'_Sy_0_K		60.3 %	17.9 %	6.2 %	80.7 %
MS2'_Sy_0.6_K		39.6 %	34.2 %		56.9 %
MS2'_Sx_0_K		11.2 %	46.7 %		57.9 %
MS2'_Sx_0.6_K				1.0 %	1.0 %
MS1'_Sy_0_K		67.9 %	11.8 %	7.0 %	81.7 %
MS1'_Sy_0.6_K		48.0 %	26.7 %	23.5 %	71.9 %
MS1'_Sx_0_K	14.7 %	18.2 %	37.1 %		71.1 %
MS1'_Sx_0.6_K		8.5 %	22.0 %		30.7 %

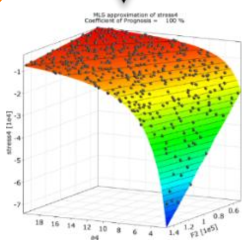
Parameter

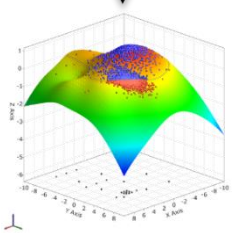
Optimization – objective function for calibration

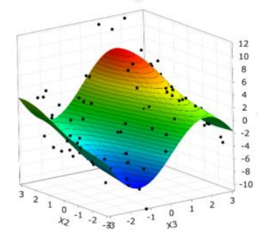
Obj = Obj_Uz + Obj_MS_Sx + Obj_MS_Sy + Obj_MS_Sz + Obj_MS´_Sx + Obj_MS´_Sy + Obj_MS´_Sz [%]

Optimization process → best fit for distortion and stress

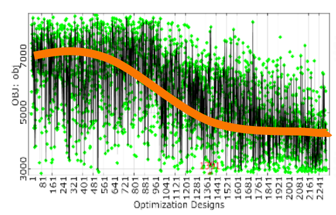








objective function MIN → best fit



MOP Solver

Reduction of calculation time

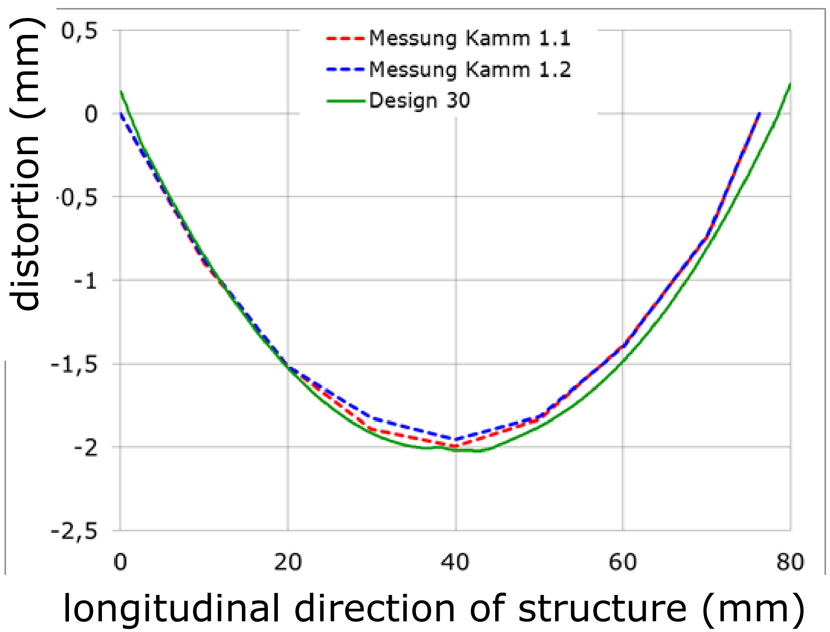
MOP-process 2300 designs → 1 h

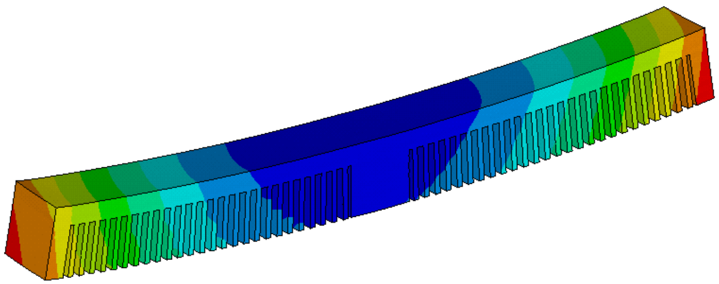
ALM – ANSYS optiSLang Workflow

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