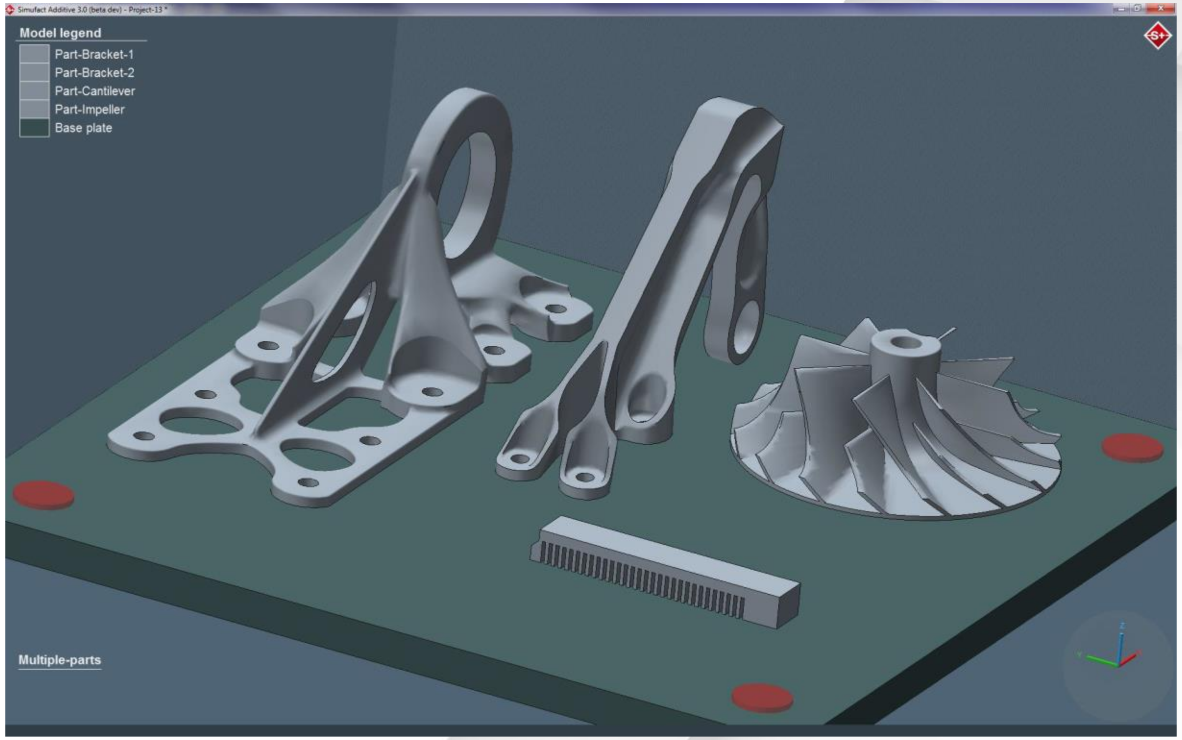
16th Annual AIAA Southern California Aerospace Systems and Technology (ASAT) Conference

Metal Additive Manufacturing Simulation – Printing It Right the First time



Hanson Chang
MSC Software Corporation
November 9, 2019

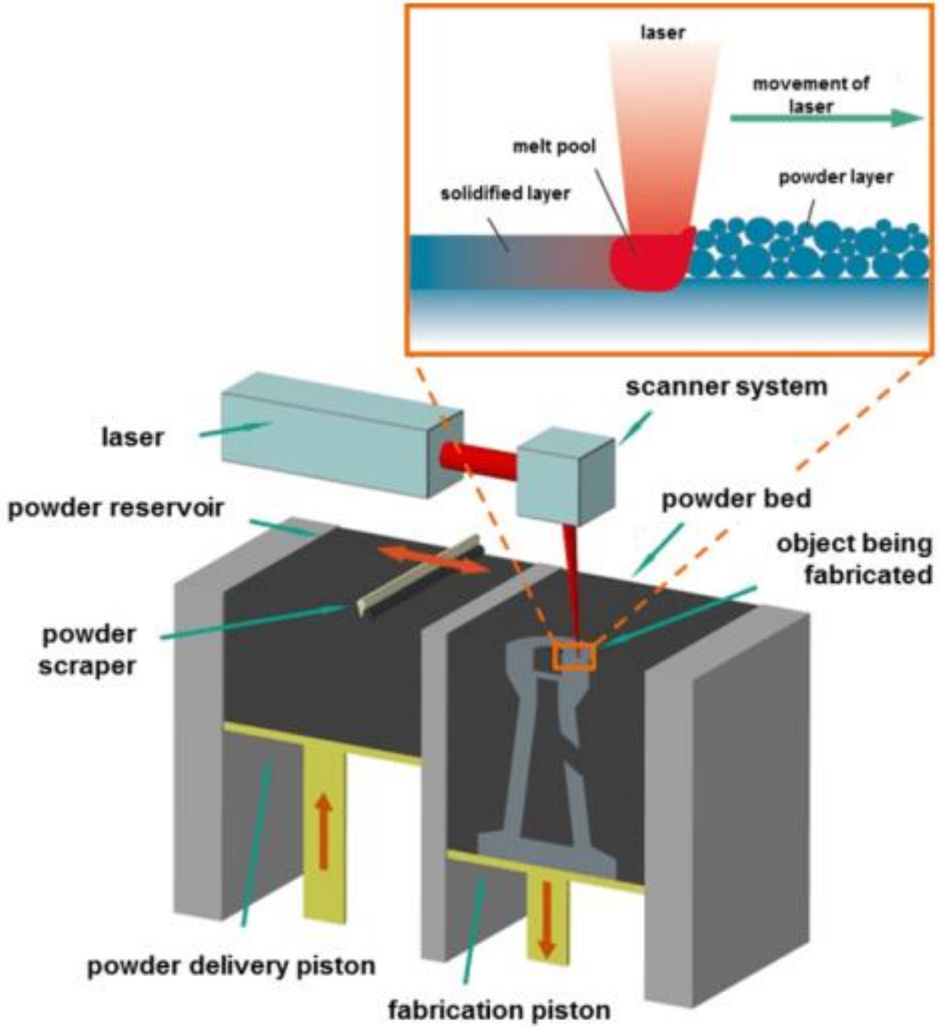
Agenda

1. Challenges to the Metal Additive Manufacturing (AM) Process
2. Pure Mechanical Simulation
3. Thermal and Thermo-Mechanical Simulation
4. What do you do with the mechanical and thermal analysis results?
5. Summary and Outlook

Additive Manufacturing - Powder Bed Fusion (PBF)

- **Several types of PBF printing techniques**
  - Selective Heat Sintering (SHS)
  - Selective Laser Sintering (SLS)
  - Electron Beam Melting (EBM)
  - Selective Laser Melting (SLM)
  - Direct Metal Laser Sintering (DMLS)

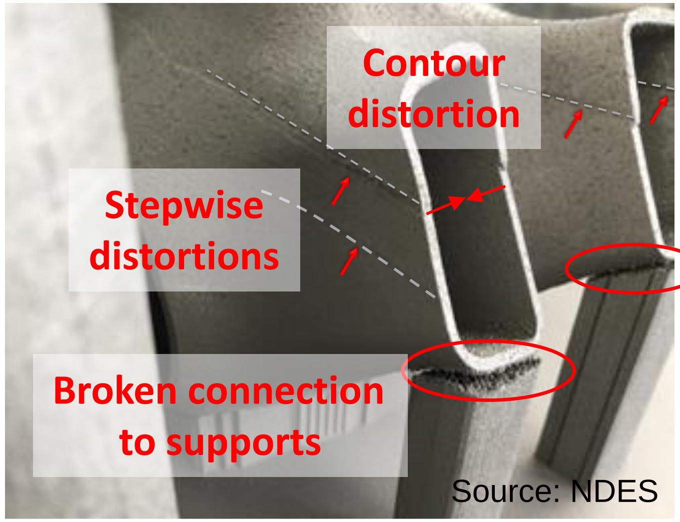
Focus of Today's Presentation

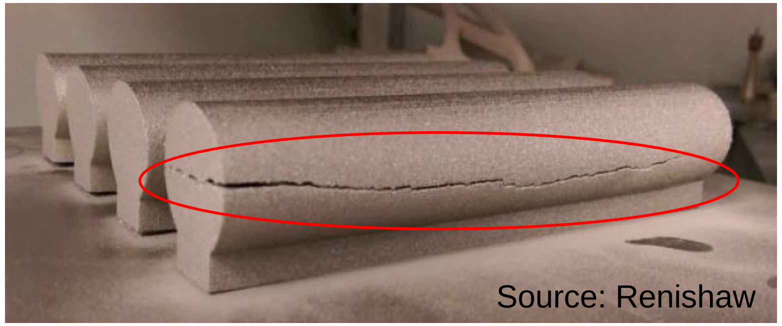


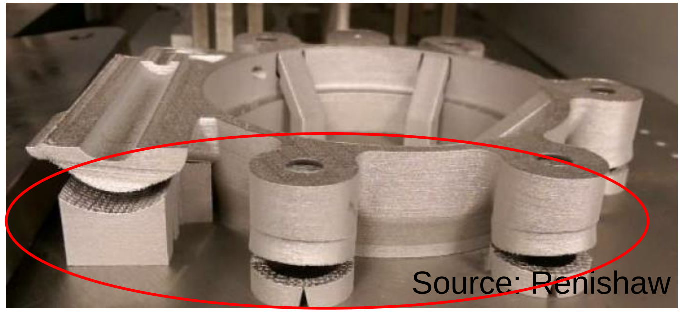
Metal Addtive Manufacturing Challenges

Major pain points

- **Distortion**
  - → Part out of Tolerances
  - → Collision with Powder Scraper
- **Residual Stresses**
  - → Part or Support Failure during Manufacturing
- **Quality**
  - → Defects, Porosity, Microstructure...



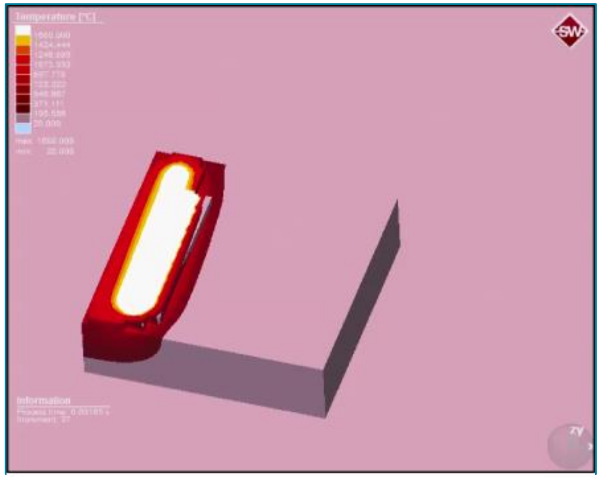


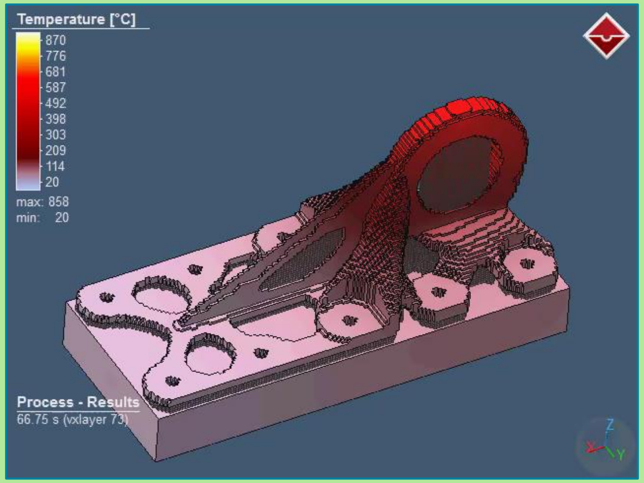


AM Simulation Methods

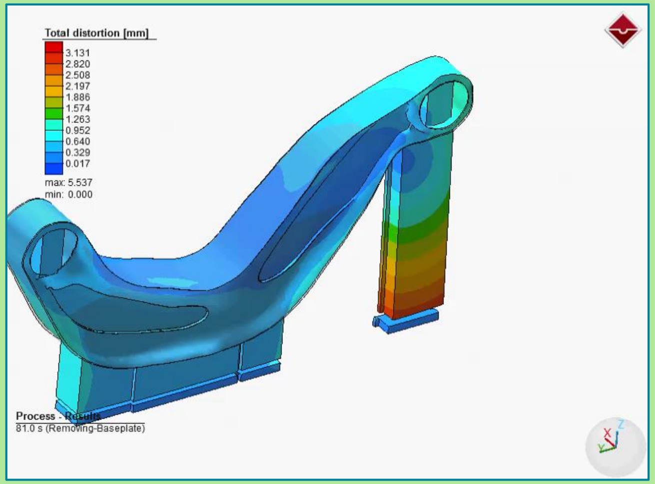
Speed

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





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



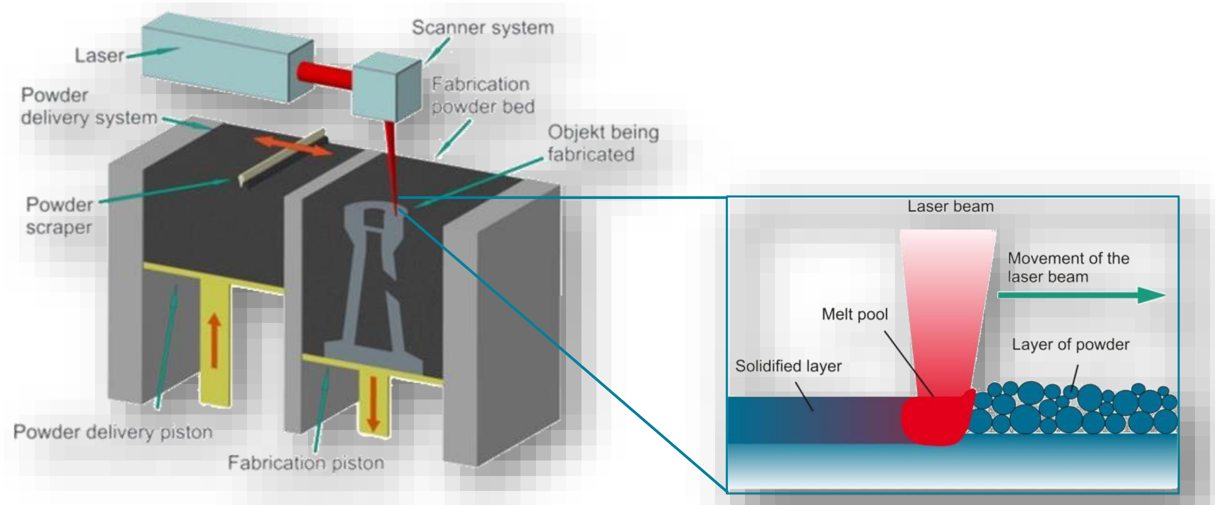
- Element layer (> powder layer) analyzed in one step
- Inherent Strains - pure mechanically, extremely fast
- **Delivers Distortion & Stress ✓**

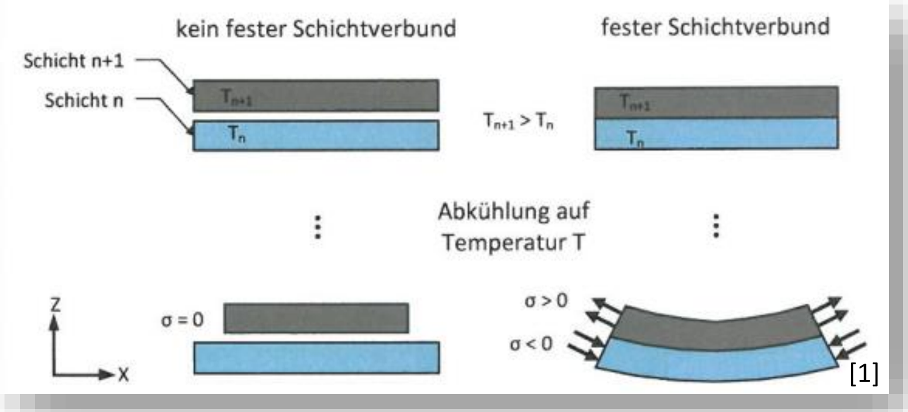
Length scale

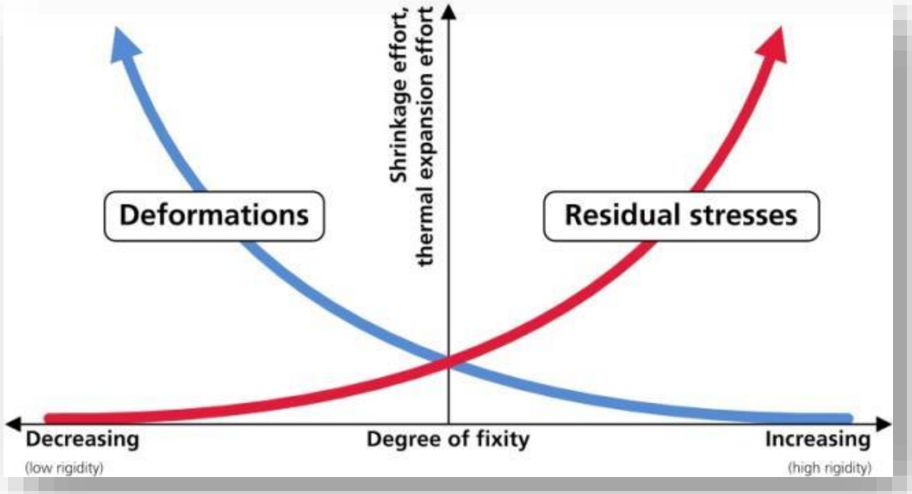
Micro scale | **Meso scale** | **Macro scale**

Macroscopic Analysis
- Pure Mechanical Analysis

Macroscopic Mechanical Analysis







- Simple model: an AM layer shrinks due to cooling.
- This implies internal stress and/or distortion.
- The average induced strain per layer is called ***inherent strain***.
- If the inherent strain is known it can be used as load in a *pure mechanical analysis.*

What are Inherent Strains?

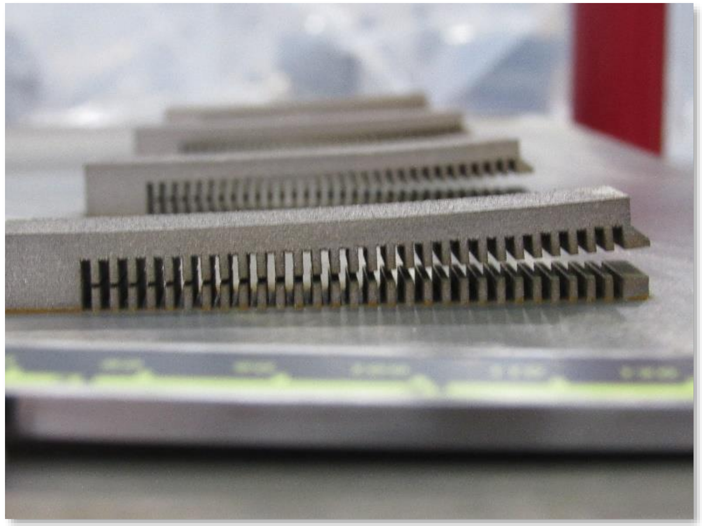
Inherent Strains

- **Originated from the welding industry**
- **Consists of**
  - Plastic strains ε^p
  - Thermal strains ε^T
  - Creep strains ε^C
  - Phase transformation strains ε^{tr}

The inherent strain ε^* consists of

$$\varepsilon^* = \varepsilon^p + \varepsilon^T + \varepsilon^c + \varepsilon^{tr}$$

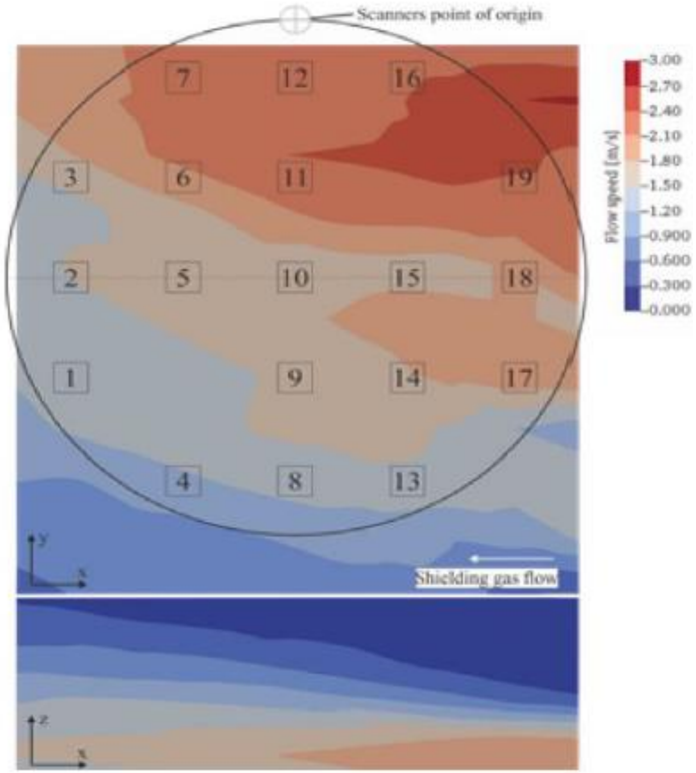
- **Reflects**
  - Material used
  - Manufacturing parameters (Laser power, scanning speed, focus diameter, scanning direction, hatching pattern, layer thickness, etc.)
  - Machine used
- **Inherent strains can be reverse engineered from test deflection results**



Calibratin Test

Inherent Strains – Build Space Variability

- **Many aspects of metal AM process result in variation across the build space**
  - Gas flow
  - Multi laser calibration
  - Multi laser stitching/overlap
  - Edge/corner effects
  - Laser plume
  - Others
- **The calibration method needs to account for this variability**
  - Inherent strain calibrations need to be performed at multiple points on plate

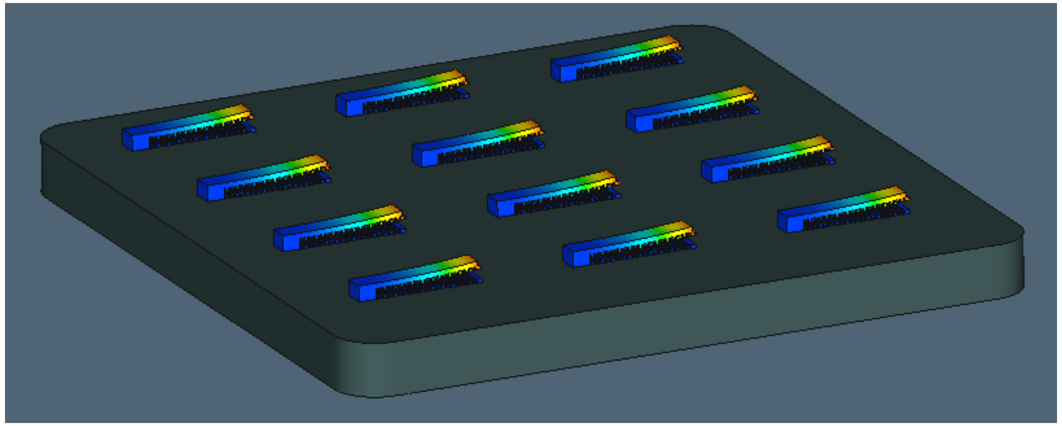


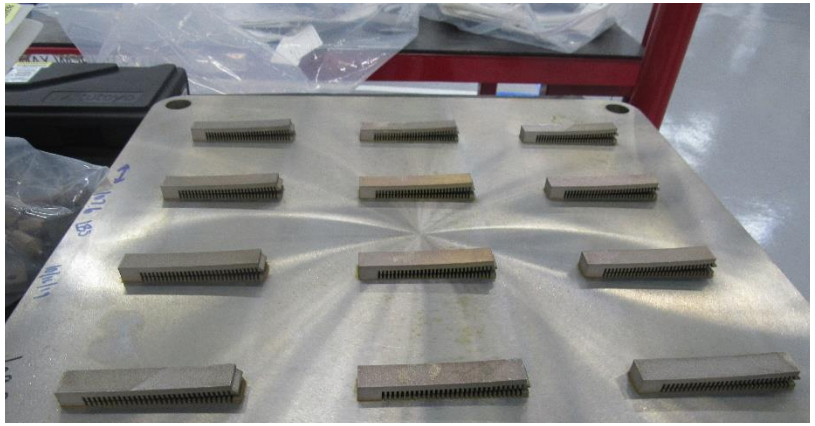
Measured shielding gas flow velocity distribution*

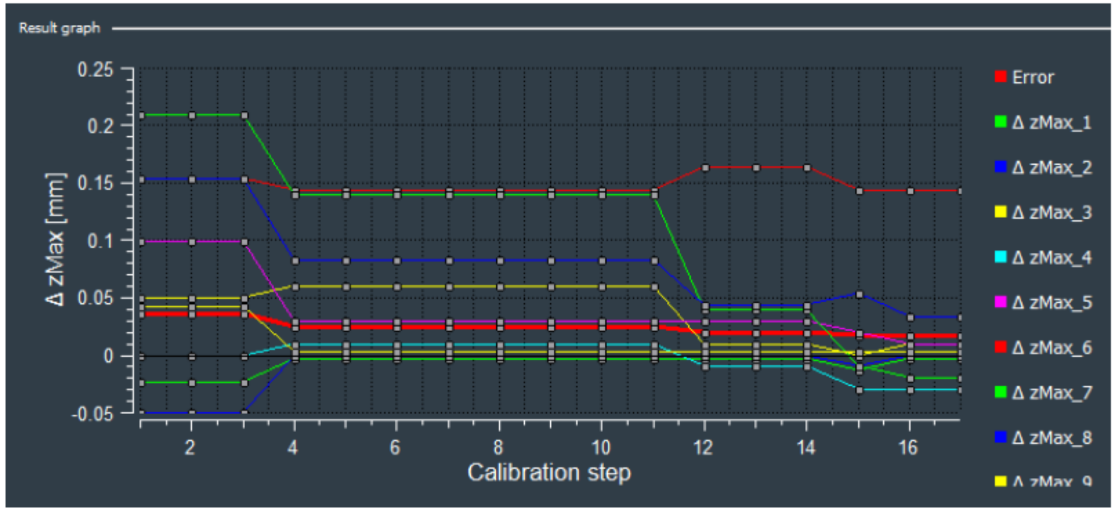
*Schniedenharn, M.; Schleifenbaum, J.H.: On the Correlation of the Shielding Gas Flow in L-PBF Machines with Part Density, DDMC 2018, Berlin

Inherent Strains – Build Space Variability

- **Inherent strains vary across the build space**
  - Build calibration specimens across build space
  - Cut and measure to calculate “inherent strain” for each X, Y region
  - Spatially variable Inherent strains are saved and applied to part level simulation

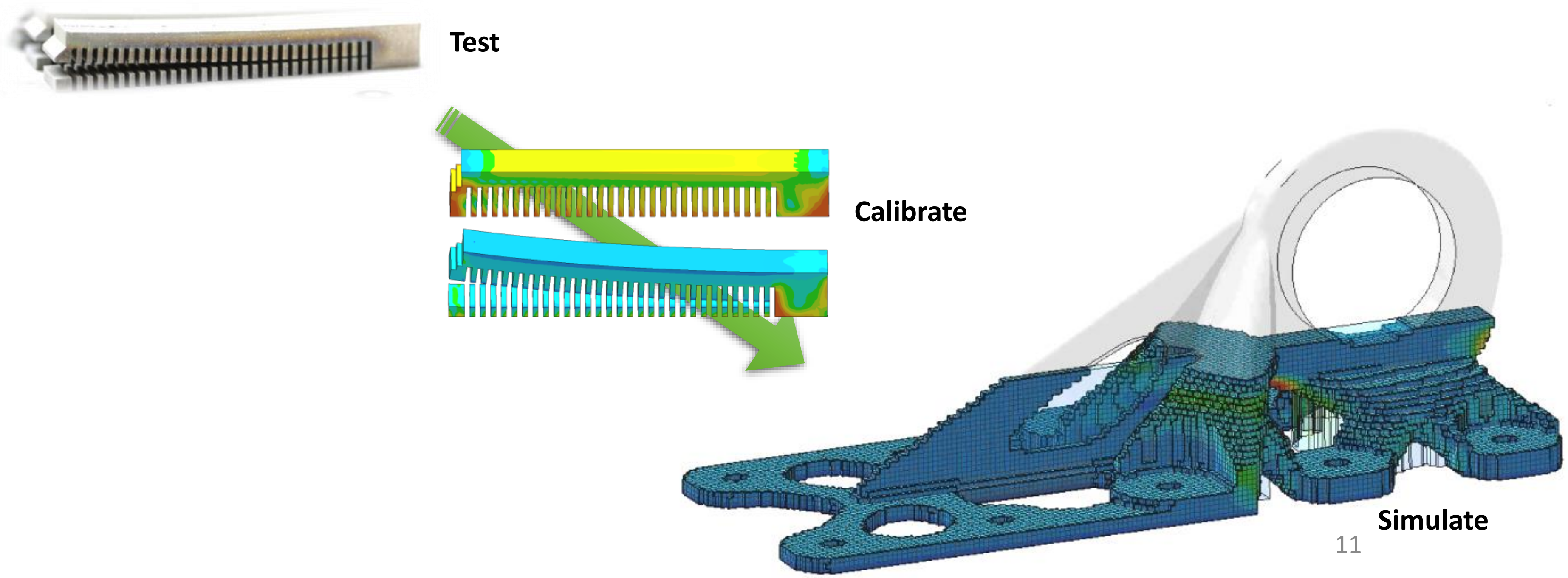






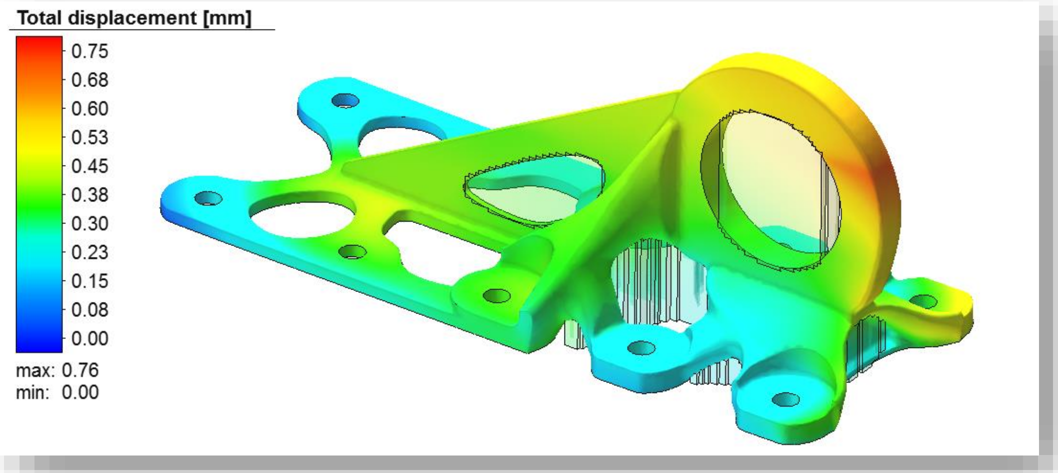
Macroscopic mechanical analysis - Workflow

- **Analysis Worklow**
  - Test - build test specimen, cut, measure deformation
  - Calibrate – reverse engineer inherent strains from test deflections
  - Simulate - activate element layers and apply inherent strains

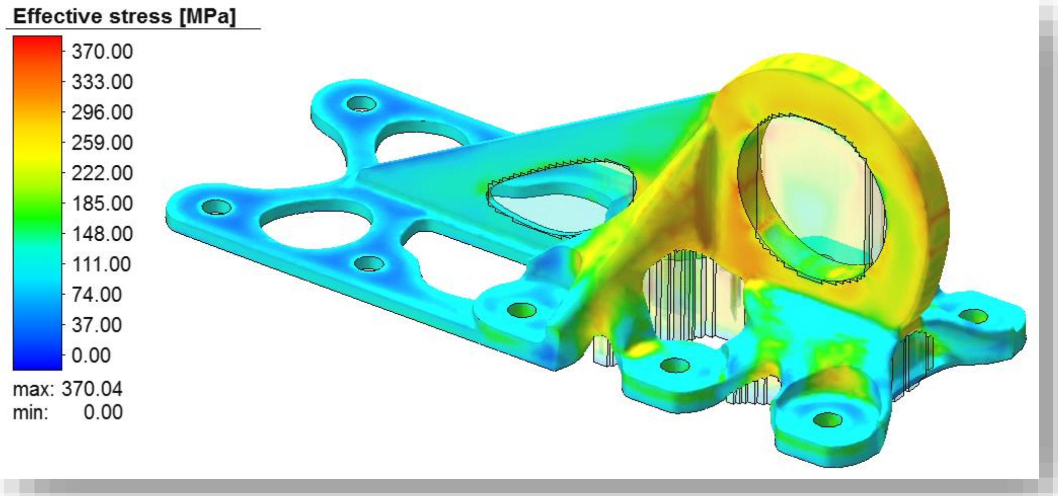


Macroscopic Mechanical Analysis Results

Real part



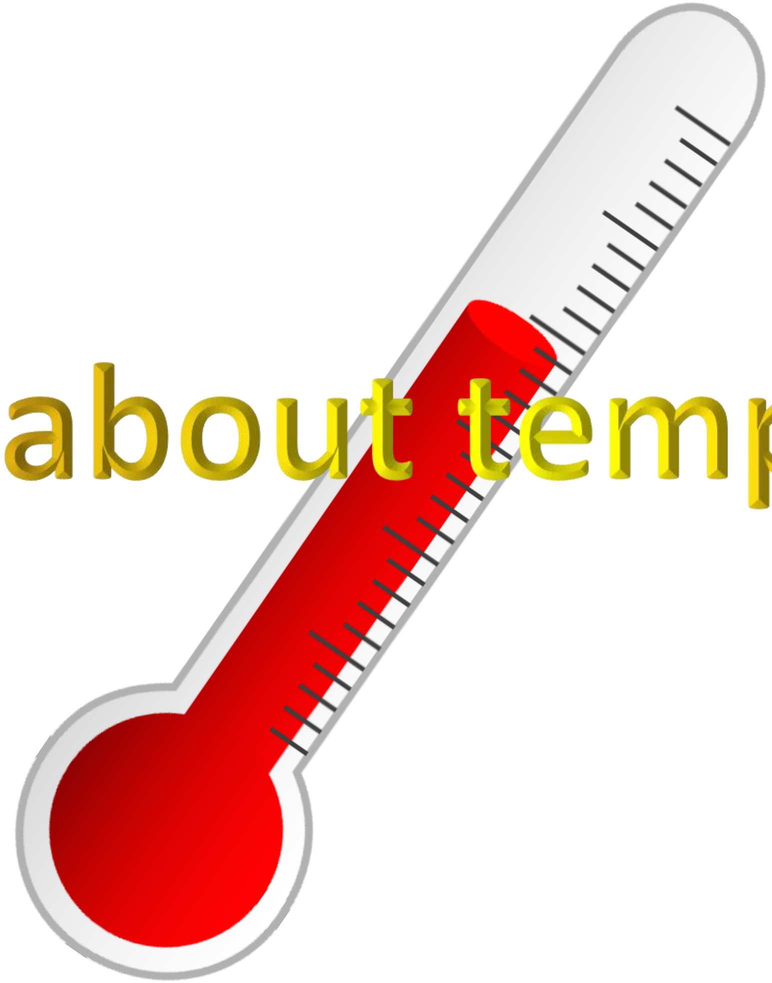
Simulated part – total displacement



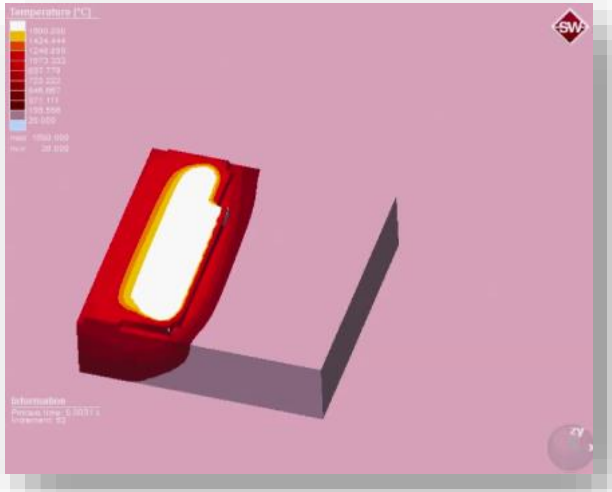
Simulated part – effective stress (von Mises)

- 0.8 mm voxels
- 160k elements
- 8 CPUs
- 30 min

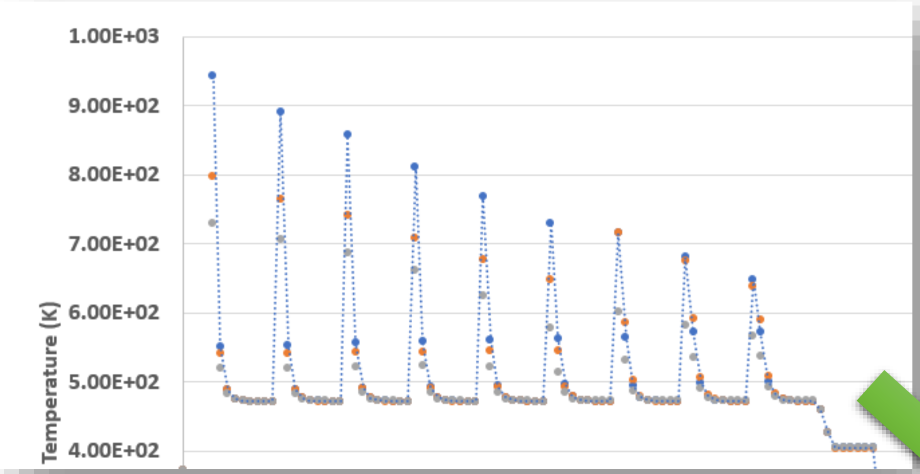
But what about temperatures?



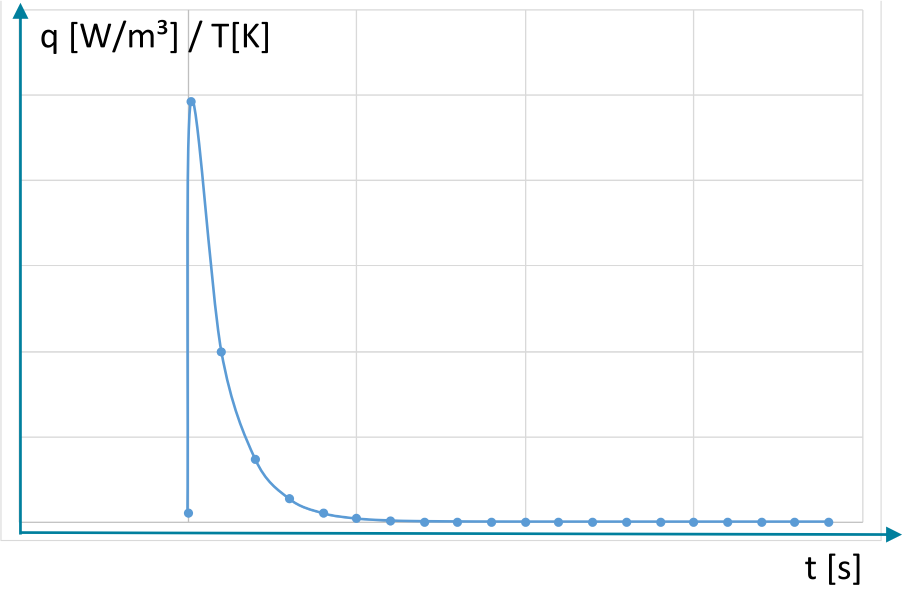
Microscopic thermal analysis



Moving heat source simulation

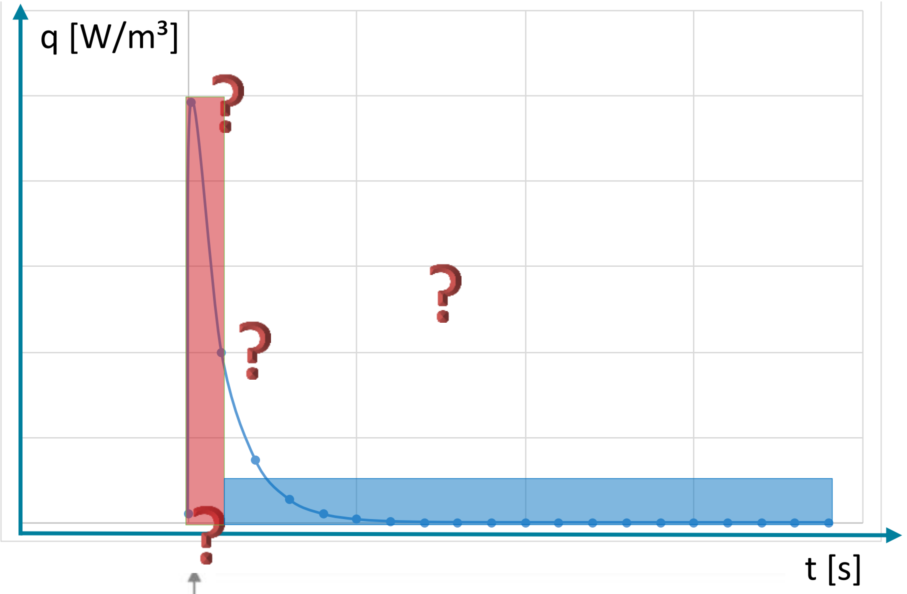


Temperature history



- Moving heat source simulation on powder layer delivers detailed thermal history.
- But: it is too time & memory consuming for real parts.
- Simplified equivalent faster model needed!
- E.g. single heat flux / thermal cycle over time per layer.

Macroscopic thermal analysis

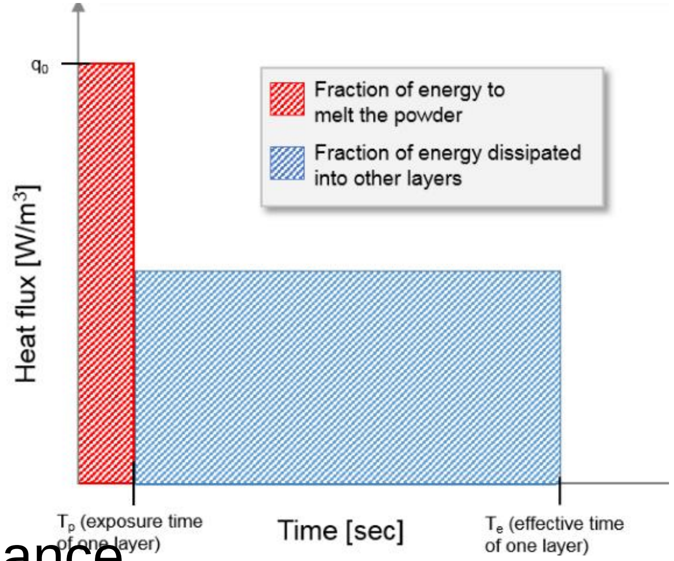


Challenges of single heat flux cycle

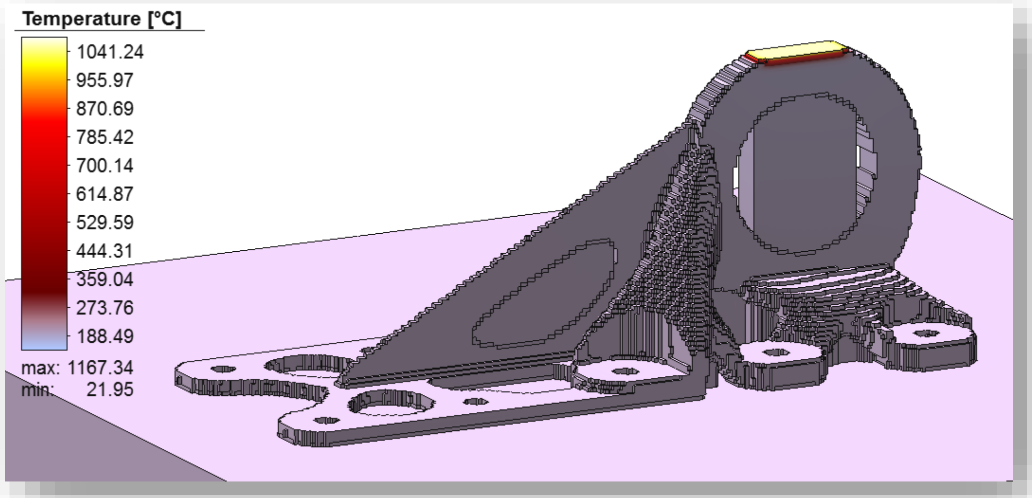
- Ensure correct energy balance with discretized steps & high heating and cooling gradients.
- How much is the maximum heat flux?
- When is the maximum heat flux?
- How does the heat flux drop down?

Solution

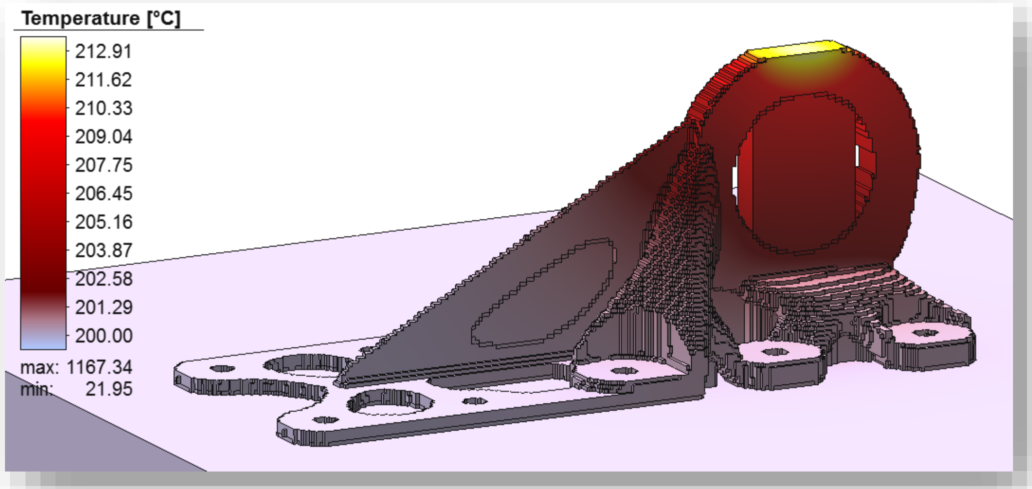
- Even more simplification!
- Two phases:
  - Primary energy application → Melting
  - Secondary energy application → Heating
- Constant heat flux per phase
- Easy to determine times → derive heat flux to keep energy balance



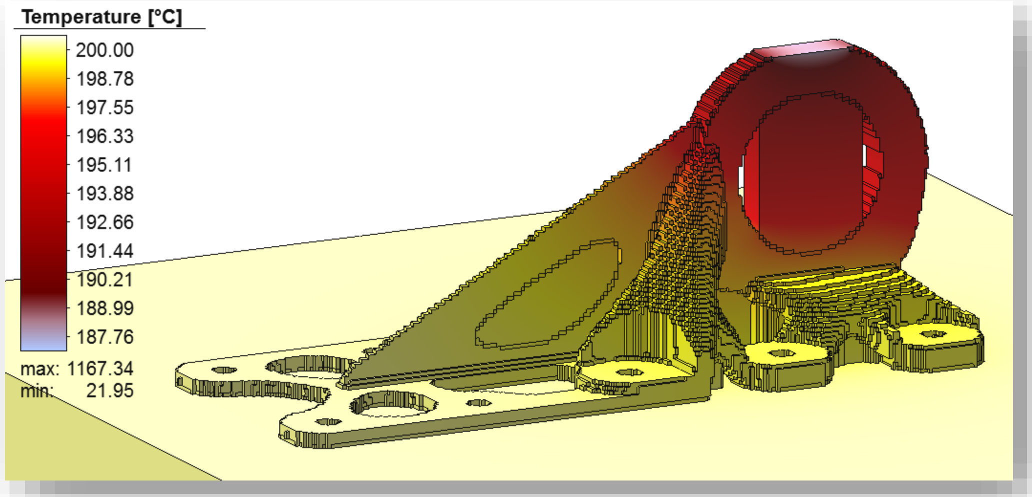
Macroscopic thermal analysis



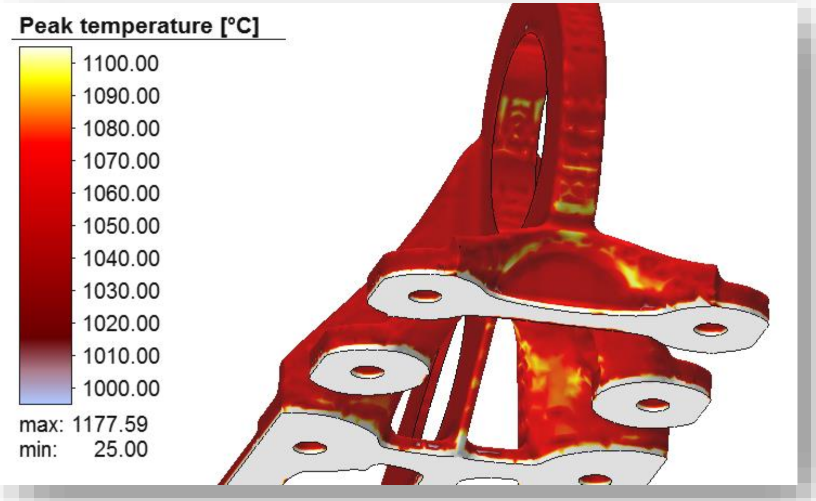
Primary heat flux application – melting



Secondary heat flux application – dissipation from top to bottom



Cooling between layers (recoating time)

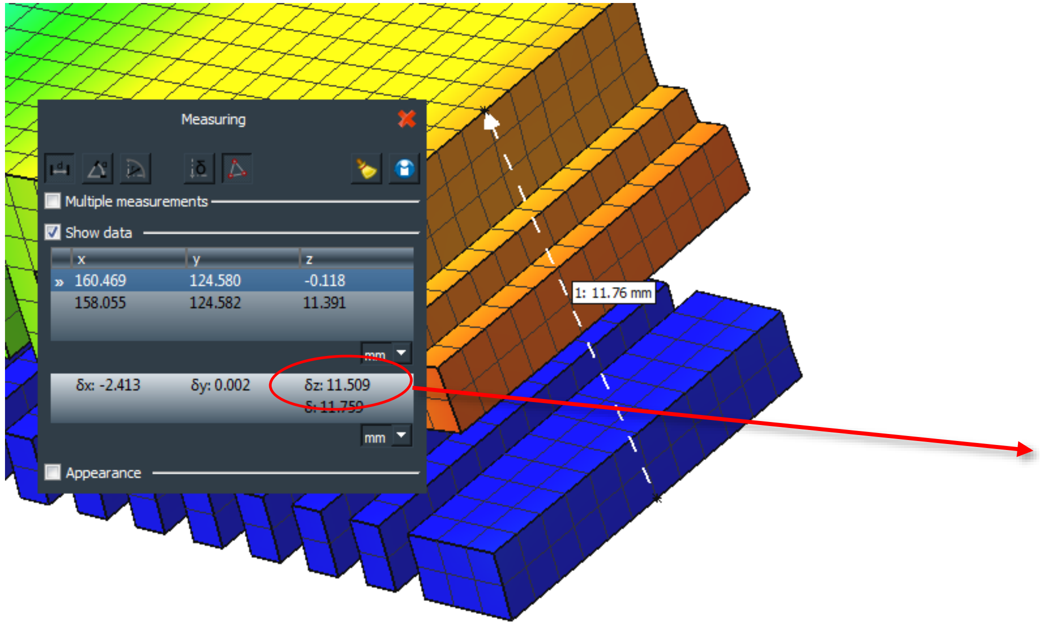


Peak temperature – over- & underheated zones

- 0.8 mm voxels
- 160k elements
- 16 CPUs
- 4 hrs

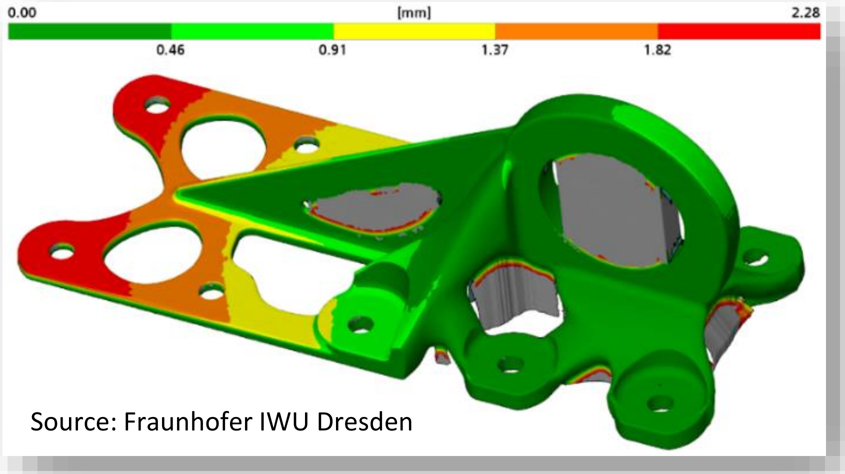
Macroscopic thermo-mechanical coupled analysis

- Once thermal simulation is available, the mechanical coupling is straightforward.
- A calibration of the peak temperature is recommended.
  (via efficiency & melting energy fraction)
- A calibration of the distortion is recommended.
  (via an expansion/shrinkage scale factor)

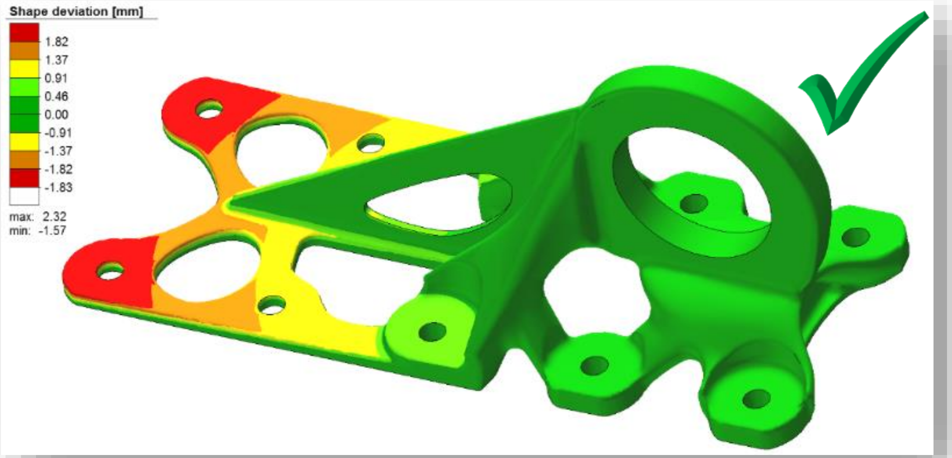


- Measured z-displacement of cantilever specimen at front tip was 2.51 mm.
- Calibrated shrinkage factor leads to same z-displacement.
- z = 11.509 mm, h = 9 mm →
  $\Delta z = z - h = 2.509$ mm ✓

Macroscopic thermo-mechanical coupled analysis



Optical measurement – surface deviation



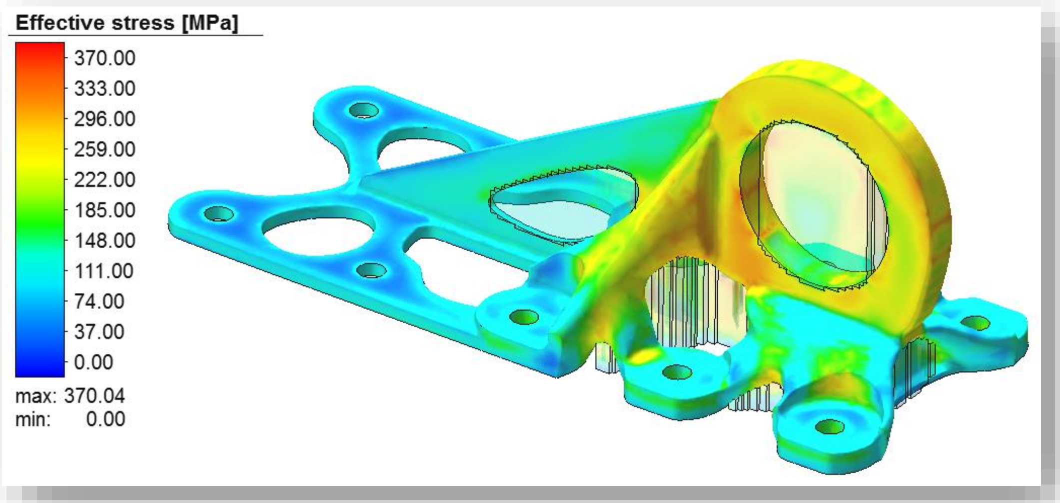
Mechanical analysis

Thermo-mechanical coupled analysis

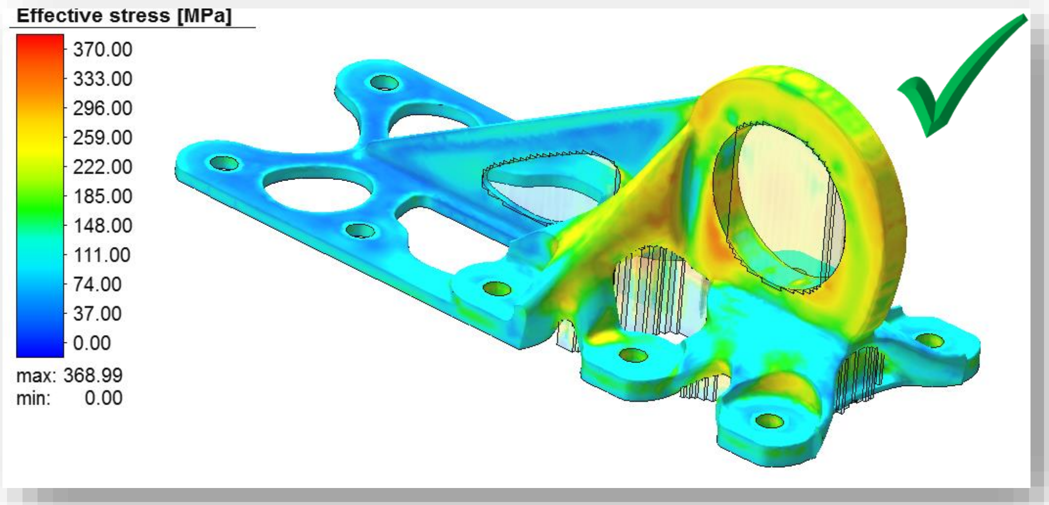
- 0.8 mm voxels
- 160k elements
- 16 CPUs
- 10 hrs

Macroscopic thermo-mechanical coupled analysis

Effective Stress (von Mises)



Mechanical analysis



Thermo-mechanical coupled analysis

Observations

- T-M analysis can deliver very similar results compared to the proven mechanical analysis.
- Deformation matches very well with mechanical analysis & measurement.
- Stresses show a qualitatively good match in terms of level and distribution.

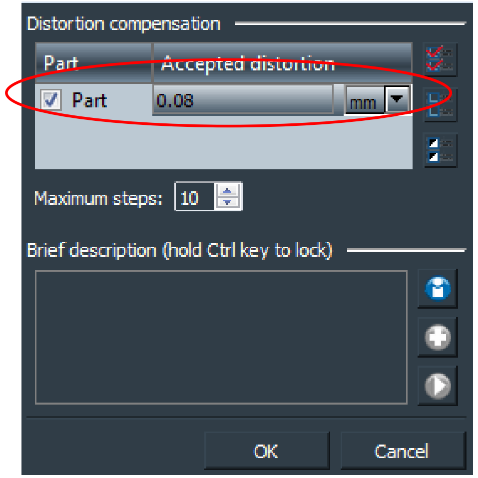
What do you do with the AM mechanical and thermal analysis results?

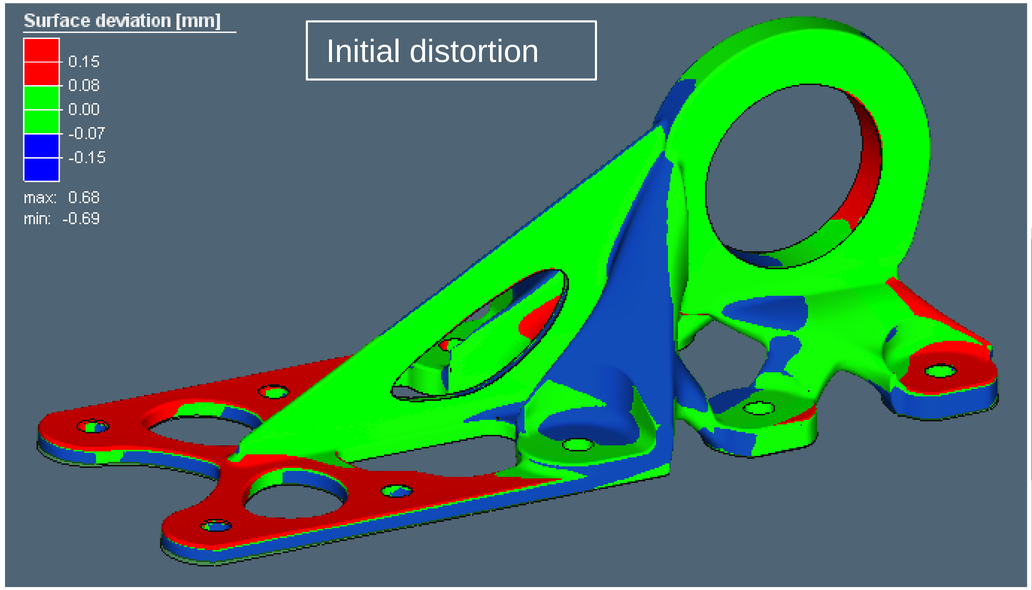
What do you do with mechanical and thermal analysis results?

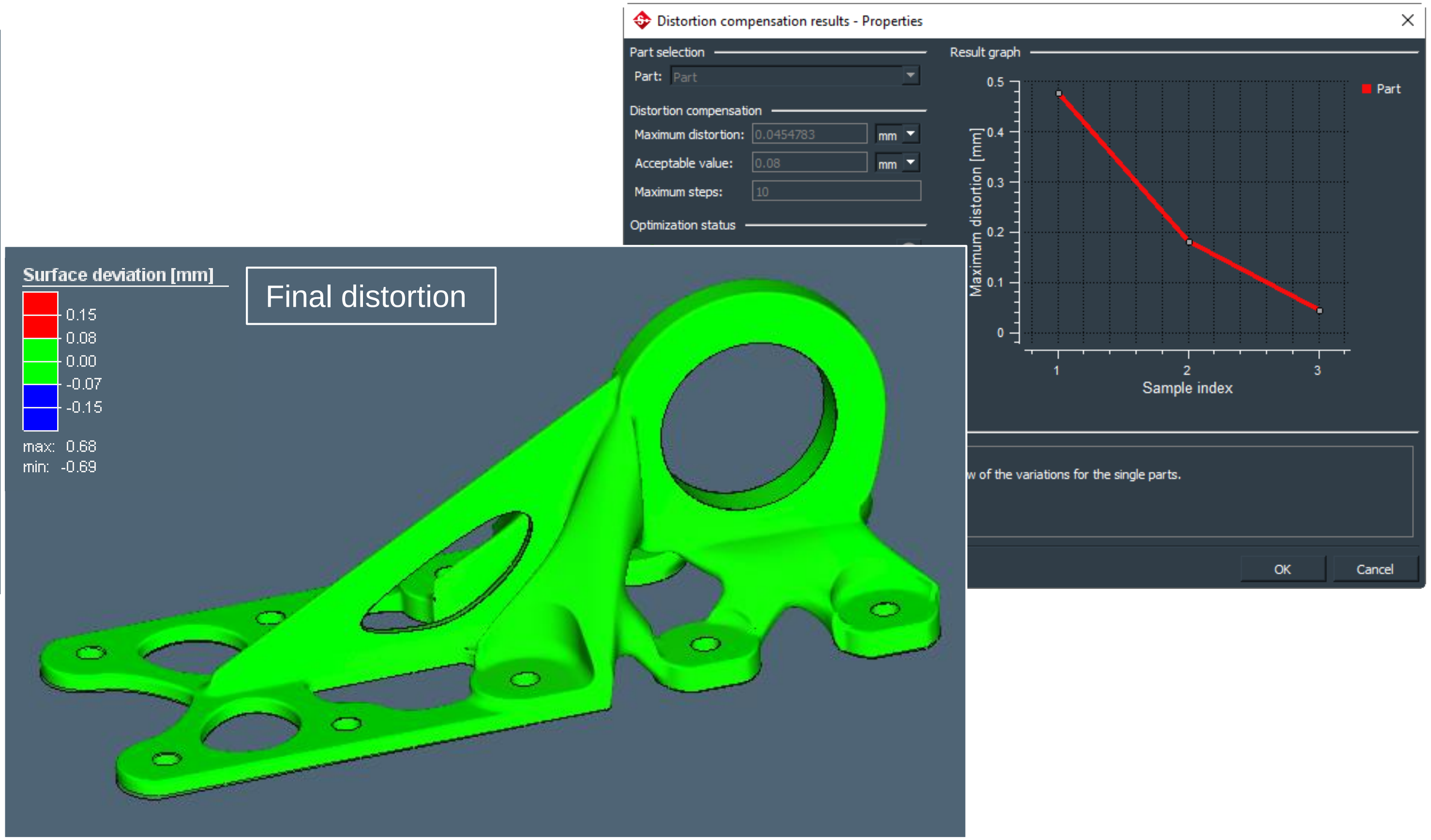
- **Distorsion results – redesign to compensate for the distortion**
- **Residual stress results – identify possible areas of breakage**
- **Thermo-mechanical results – identify hot spots and possible recoater blade contact issue**
- **Parametric studies – help you dial in the optimal set of printing parameters**

Automatic Distortion Compensation

- A negative sign is applied to the deformed shape and is used as input to the next iteration
- This process is repeated until the final shape is within the specified distortion from the orginal design

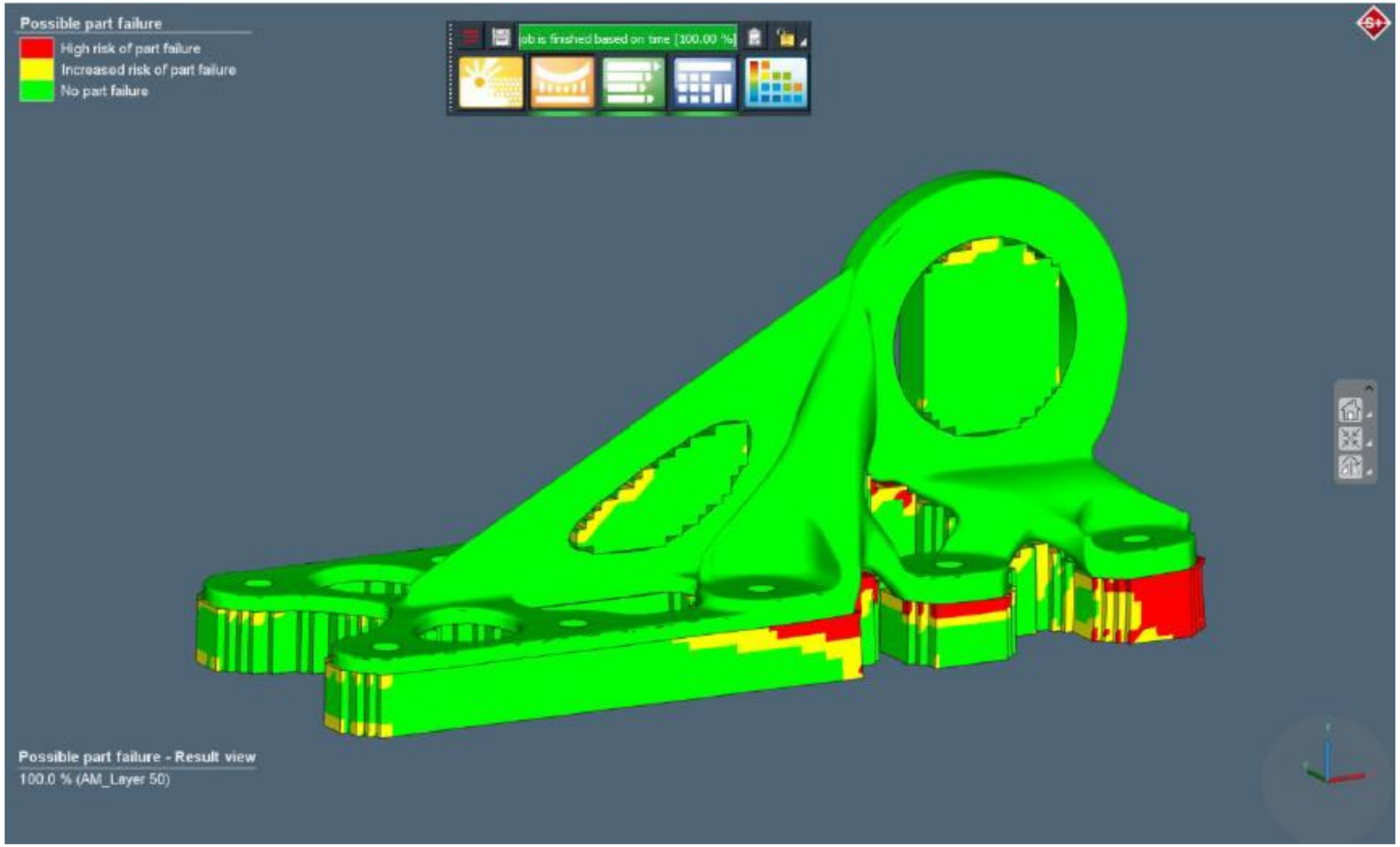






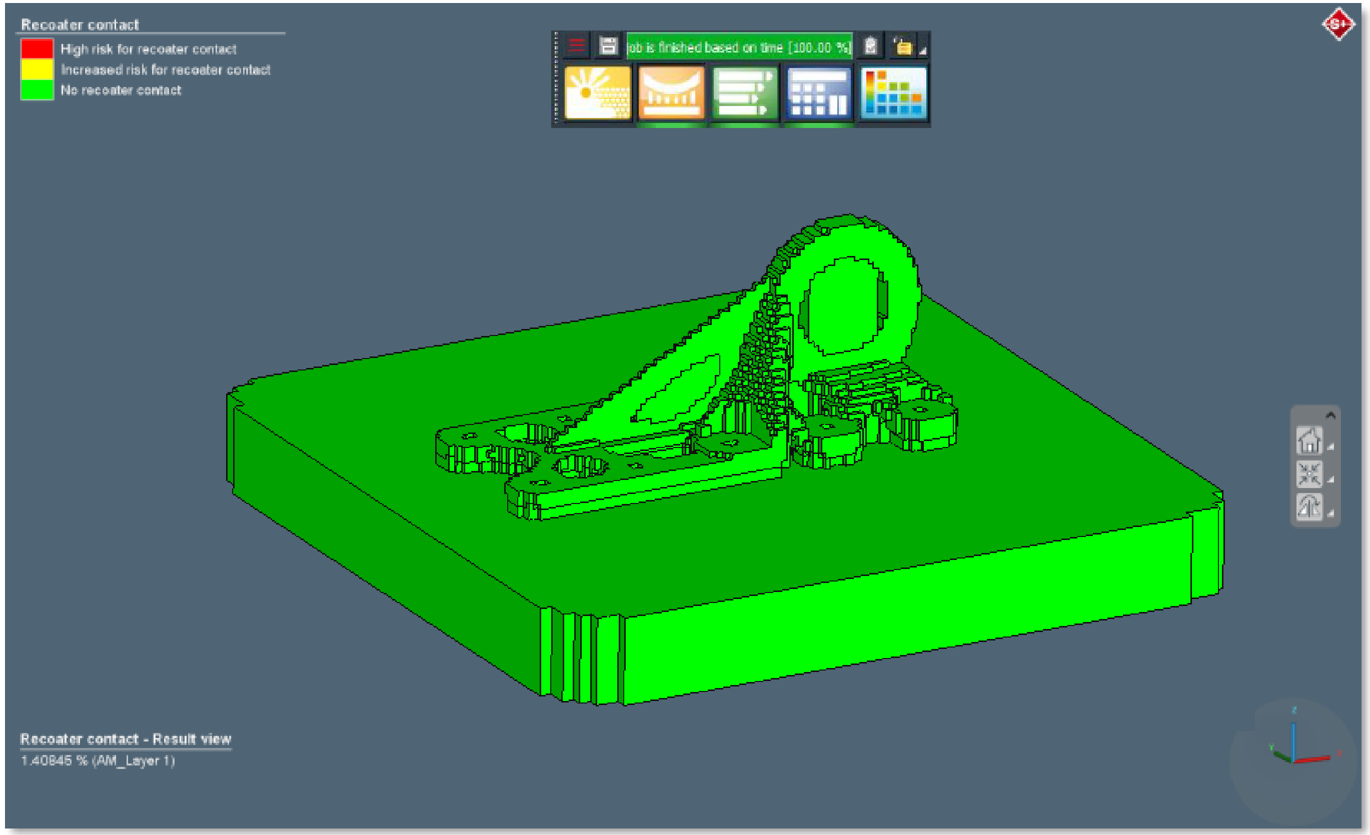
Residual Stress Evaluation

- **Identify possible part or support failure**
  - **Based on material ultimate strain**



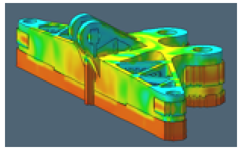
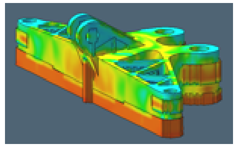
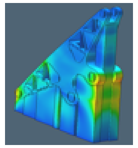
Recoater Contact Issue

- The thermo-mechanical simulation identifies thermal overload which casues the part to grow out of the powder layer and interacts with the recoater
- The Recoater Contact plot shows you the probability of collision between the recoater and part

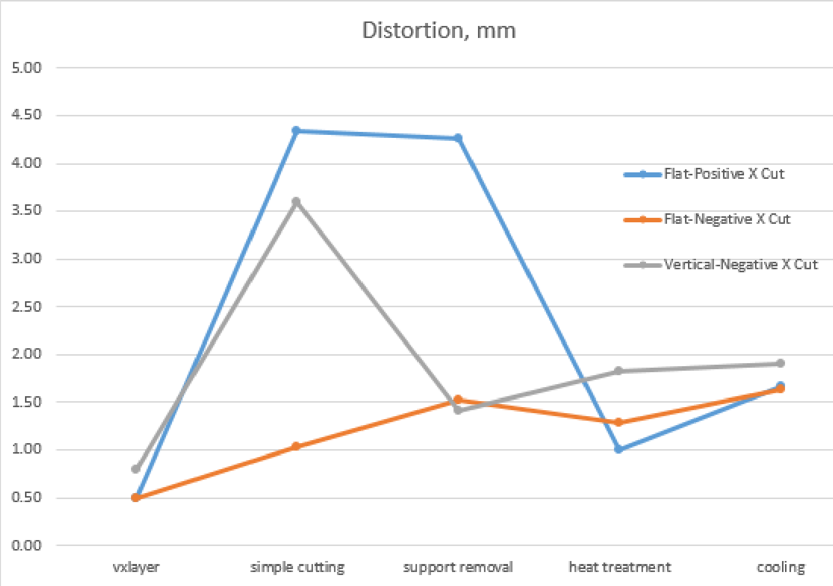


Parametric Studies

- **Parametric studies help you dial in the optimal set of printing parameters before you ever physically print the part!**
- **Mechanical Study: Different part orientations and support systems followed by different cutting sequences and heat treatment (see image below)**
- **Thermal and Thermo-Mechanical study: Different base plate temperature, laser power, laser speed, hatching distance, etc.**

	Flat-Positive X Cut		Flat-Negative X Cut		Vertical-Negative X Cut	
	Distortion, mm	Effective Stress, N/mm^2	Distortion, mm	Effective Stress, N/mm^2	Distortion, mm	Effective Stress, N/mm^2
vxlayer	0.49	1289.00	0.49	1289.00	0.79	1280.00
simple cutting	4.34	1270.00	1.04	1229.00	3.59	1271.00
support removal	4.26	1176.00	1.53	1277.00	1.42	1190.00
heat treatment	1.00	28.00	1.28	28.00	1.83	277.00
cooling	1.66	23.00	1.64	23.00	1.90	279.00



Summary & Outlook

- **Simfact Additive from MSC can perform mechanical, thermal and thermo-mechanical metal AM simulations**
- **Mechanical analysis delivers fast predictions for distortion and residual stress**
- **Thermal analysis predicts the global temperature distribution & simplified thermal history in reasonable time**
- **Thermo-mechanical coupled analysis predicts global temperature distribution, distortion & residual stress in reasonable time**
- **Under R&D – use microscopic analysis to predict material and microstructure properties**
  - Phase distribution
  - Yield strength
  - Ultimate strength
  - Hardness

Thank you!

