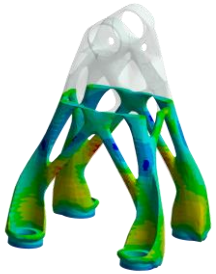
Applying Finite Elements Practices to Predict Manufacturing Distortions in a Sintered 3D printed MoldJet® Metal Part

Omri Yannay / Ansys

Ohad Dolev , Yitzhak Saydo / Tritone.

Agenda

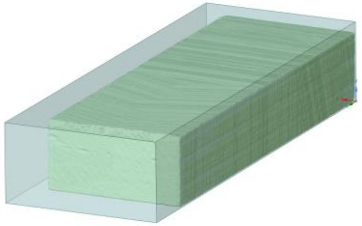
- Motivation



- Simulation Capabilities

$$\eta = AT\exp\left(\frac{B}{T}\right)\cdot\left(\frac{g}{g_0}\right)^3$$

- Theory Background

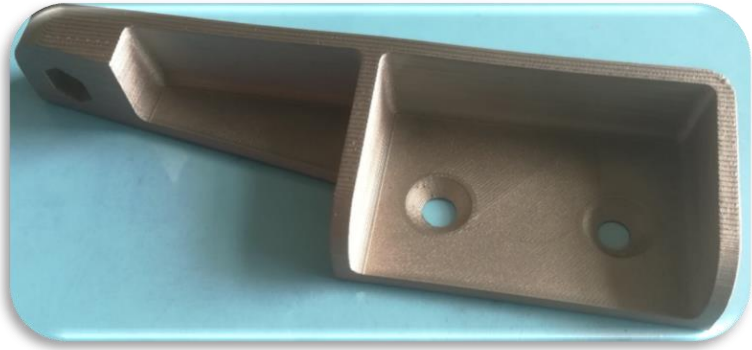


- Calibration

Case Study:

ALSTOM
• mobility by nature •

Courtesy to Alstom
LINT ©, Germany



- Sintering Simulation
- Distorsion Compensation Analysis
- Verification – Sintering Simulation of Distorted Part
- Validation- Sintering Printed Distorted Part

Background

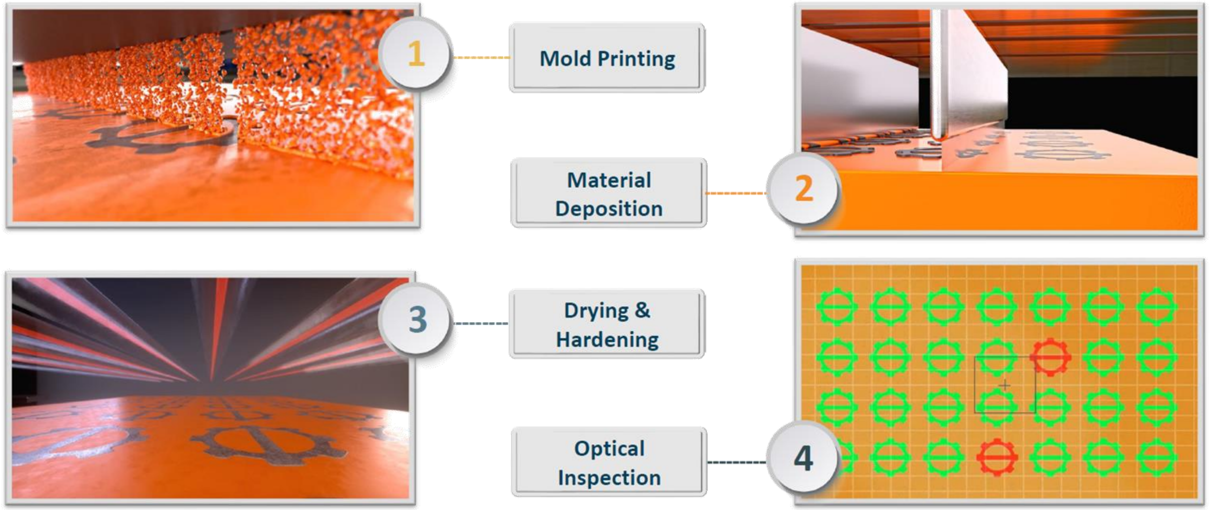
Tritone Industrial Additive Manufacturing

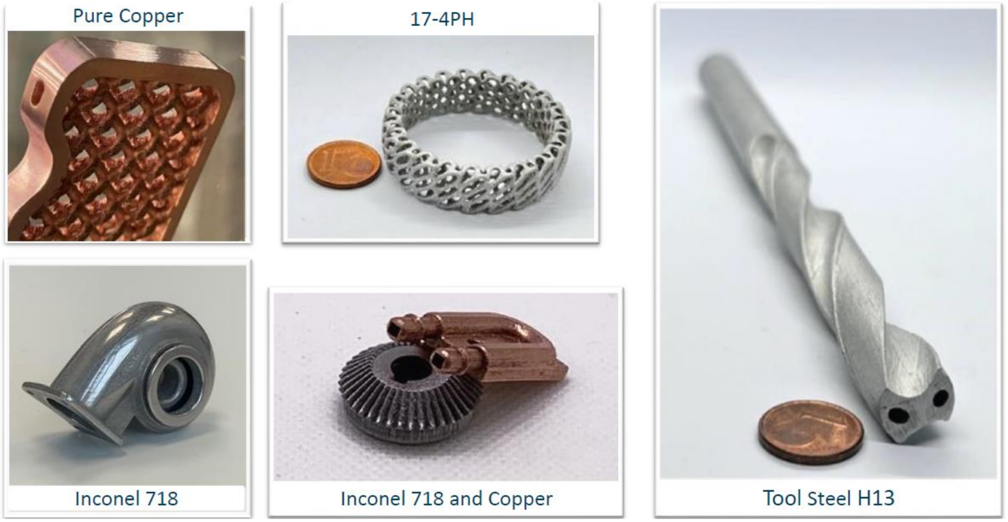
Tritone's 3D manufacturing **MoldJet®** technology process, is a sequential manufacturing process resulting with remarkable green parts dimensions and mechanical properties.

Following demolding and curing stages, the **green parts undergo a sintering process** at a temperature just below their melting point and get solidified while their density is also increased to meet standards requirements.

While being sintered, the green bodies **initial proportions** are changed and **can be reduced up to 15%.** This dimensional change is affected by parameters such as **sintering process profile**, **part geometry**, **material properties**, **part sintering orientation, and more.**

MoldJet® Process Workflow



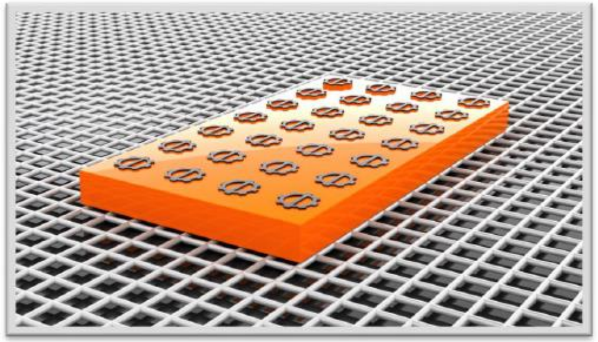


Ansys

Motivation

Finite Element Analysis (FEA) was applied using **Ansys Mechanical** and **Ansys Additive Suite**. Leveraging the FEA insights, allows understanding the **preferred parameters** for the **sintering stage**, as well as designing an **intentionally deformed green body part** to **meet** the **desired requirements after sintering.**

MoldJet® Technology



Finished Tray

Demolding Stage

Thermal Debinding & Sintering Stage

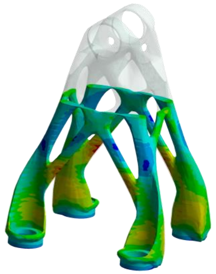
Assets final dimensions before sintering

Dimension change

Agenda

Case Study:

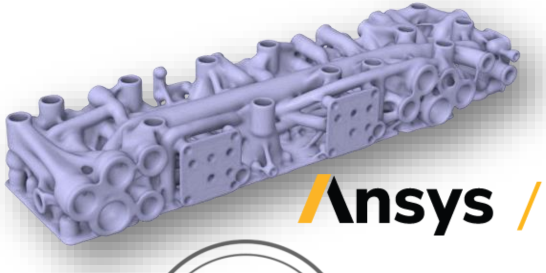
- Motivation



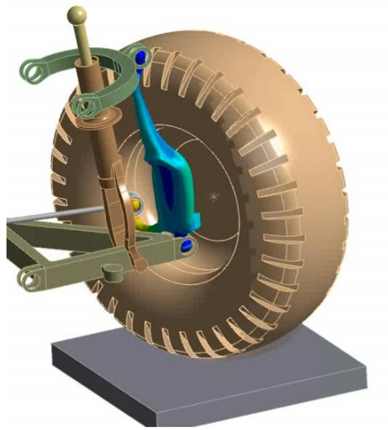
- Simulation Capabilities
- Theory Background
- Calibration

- Sintering Simulation
- Distorsion Compensation Analysis
- Verification – Sintering Simulation of Distorted Part
- Validation- Sintering Printed Distorted Part

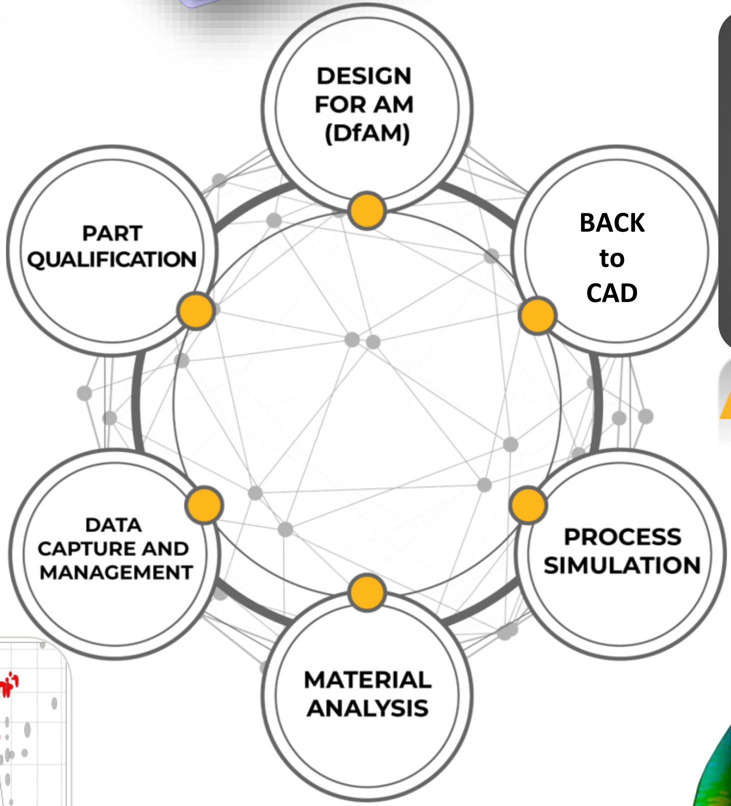
Ansys Additive Solutions

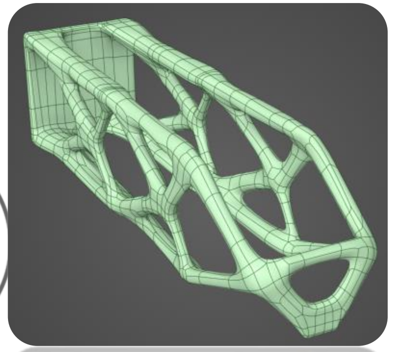


Ansys / MECHANICAL

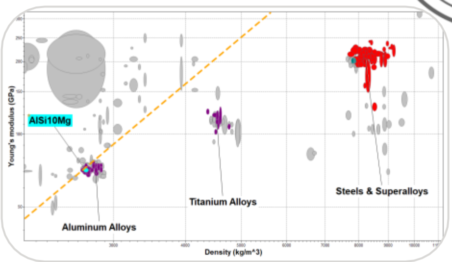


Ansys / MOTION

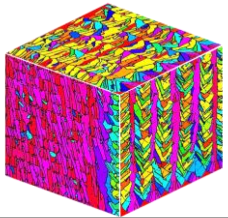


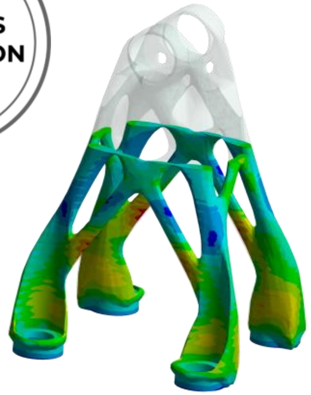


Ansys / DISCOVERY



Ansys / GRANTA



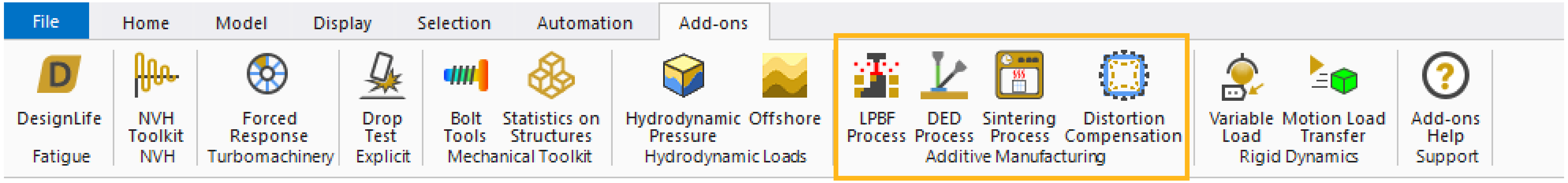


Ansys / ADDITIVE SUITE

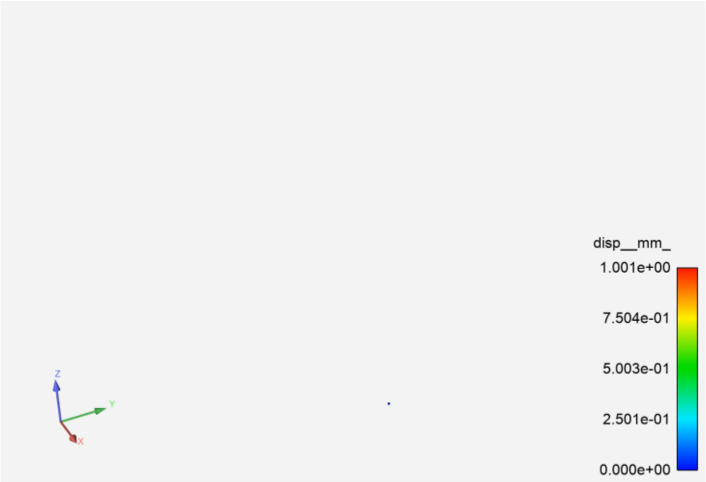
Ansys

New Additive Add-ons native in Ansys Mechanical

Ansys Learning Hub Additive Add-ons Short Tutorials

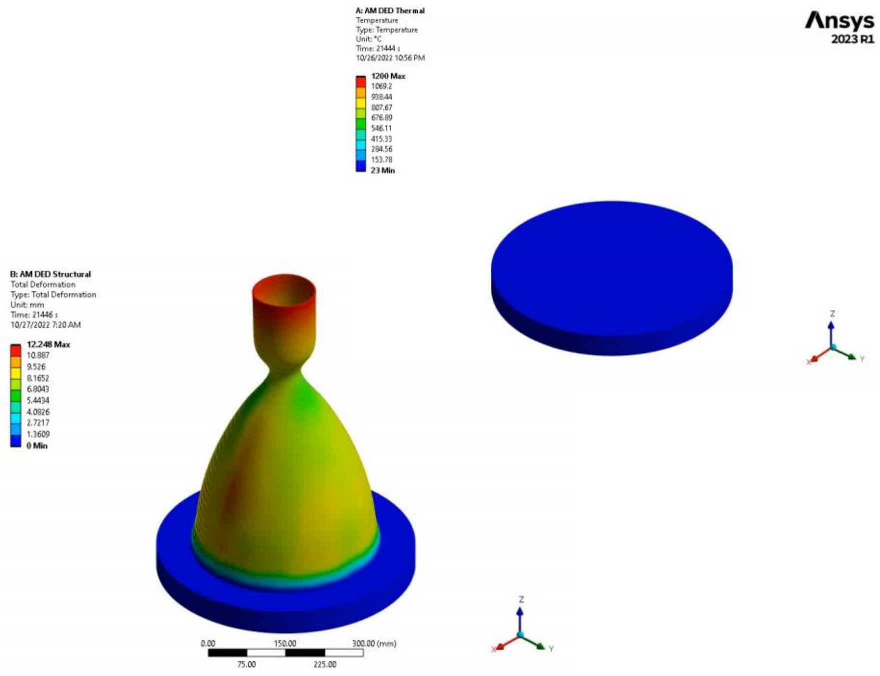


Laser Power Bed Fusion (LPBF)



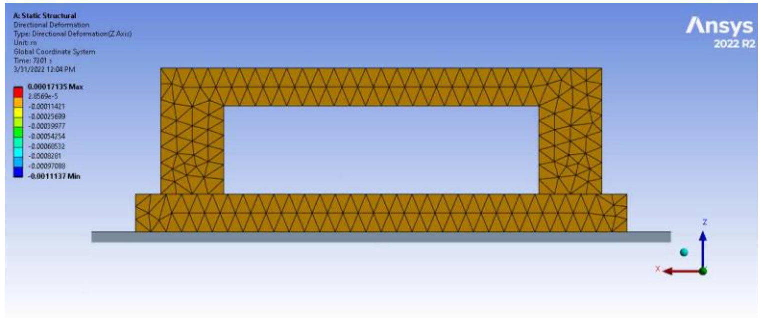
Predicted deformation

Directed Energy Deposition (DED)



Rocket motor temperature and deformation

Sintering (Binder Jetting)



Sintering shrinkage

Applications – Air Filter Distortion Compensation

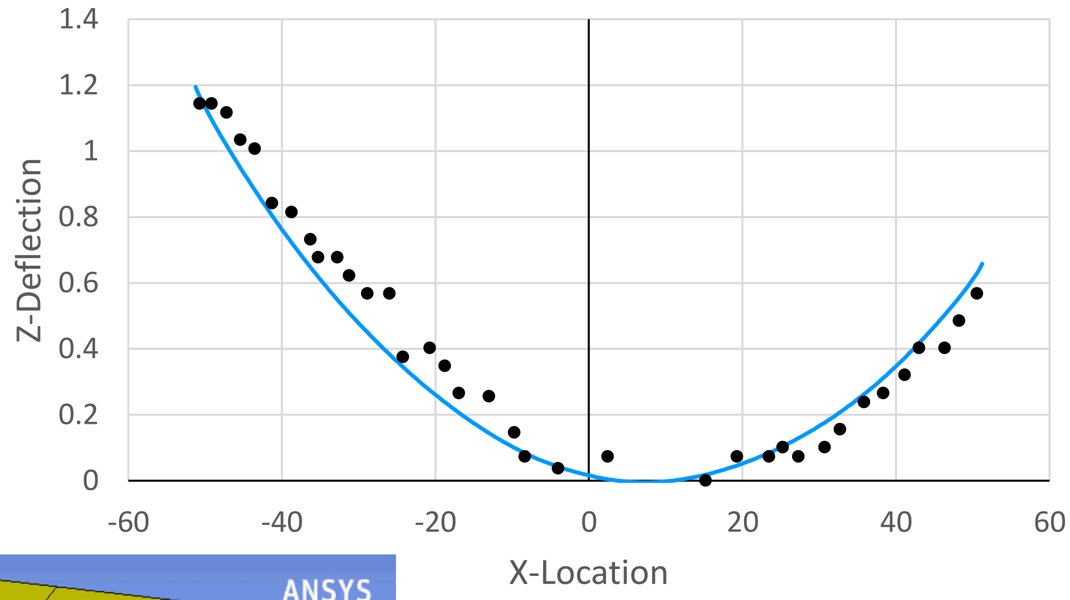
Original Geometry

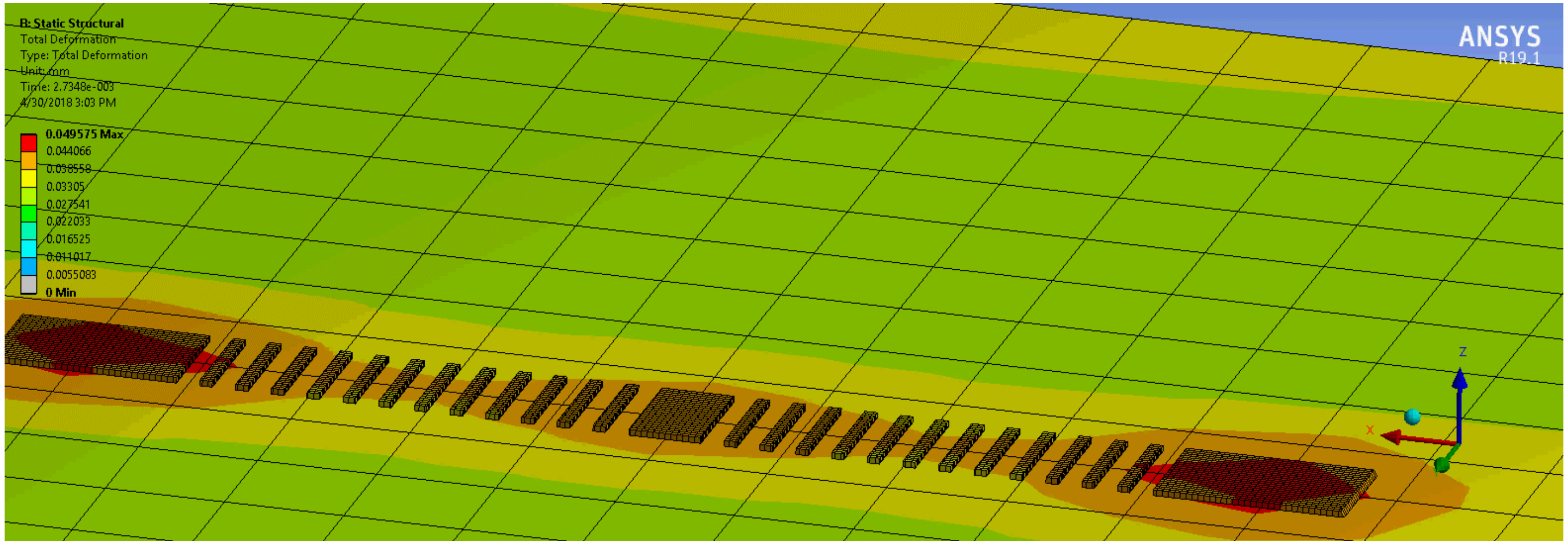
Compensated Geometry

Courtesy of Croft Filters

Support Removal – Sequence Matters

- Asymmetric deformation observed after support removal is accurately captured by simulation
- Manufacturers should take support removal order into consideration when working with AM

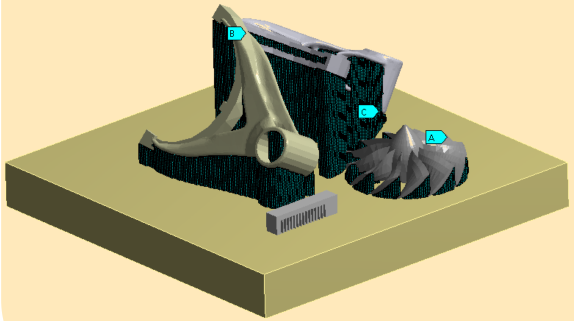




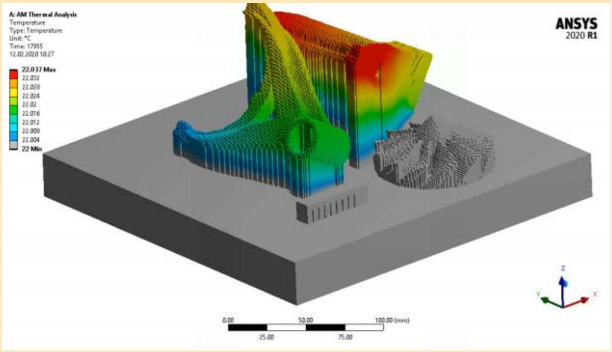
Additional Process Simulation

Tritone
Industrial Additive Manufacturing

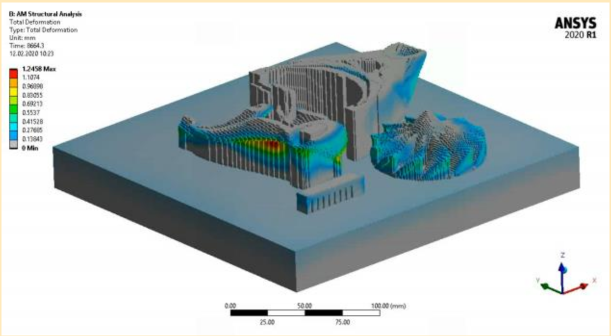
Thermo-mechanical & inherent strains

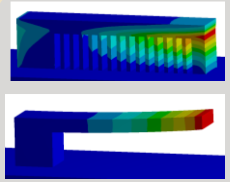


Temperature



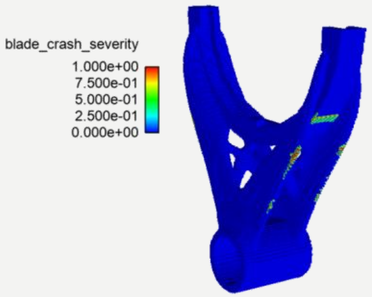
Displacement





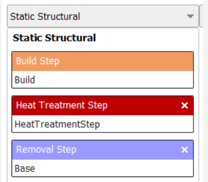
e_x, e_y, e_z

Build defects

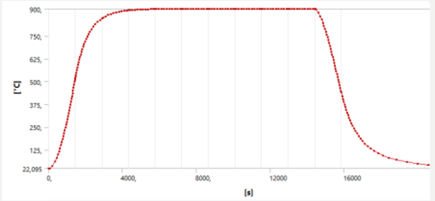


Blade crash severity, shrink lines, support failure

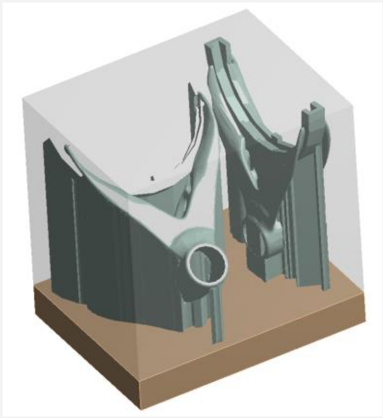
Heat treatment

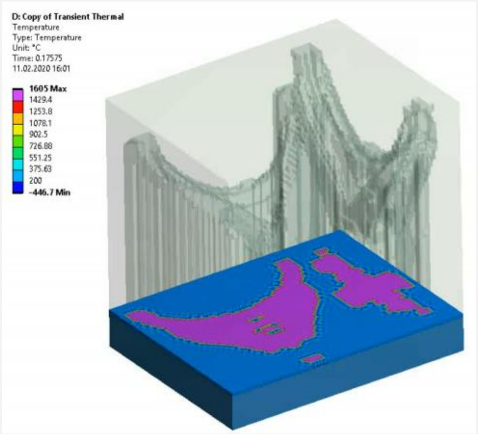


Different material models can be used to capture time-dependent deformation



Powder interaction





Ansys

Ansys / ADDITIVE SUITE

Agenda

Case Study:

$$\eta = AT\exp\left(\frac{B}{T}\right)\cdot\left(\frac{g}{g_0}\right)^3$$

- Motivation
- Simulation Capabilities
- Theory Background
- Calibration

- Sintering Simulation
- Distorsion Compensation Analysis
- Verification – Sintering Simulation of Distorted Part
- Validation- Sintering Printed Distorted Part

Calibration Challenge

Achieve similar dimensions in sintering simulation compared to manufactured

Inputs:

Geomtery

- Initial Dimension

Sintering Process:

- Thermal cycle
- Gravity Direction (Sintering orientation)
- Base plate frictional force

Material

- Sintering temperature
- Powder diameter
- Relative density (sintered/initial)

$f(\alpha, \beta, \gamma \ldots)$

Outputs:

Final dimensions measured by: (micrometer/3D scan/dilatometer)

Calibration Objectives

- Dimensional **shrinkage**
- Viscous **creep behavior** leading to **warpage or bending** of the part under **gravity**
- **Grain growth** effects (optional, depending on the material)

Advanced Calibration Methods

Tritone Industrial Additive Manufacturing

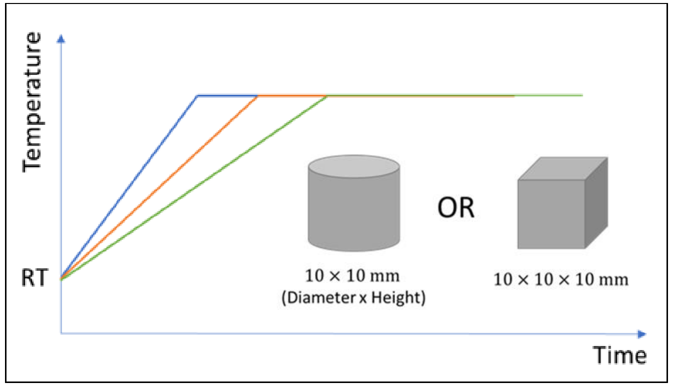
Dimensional Shrinkage	Bending under Gravity	Grain Growth Effects (Optional, material dependent)
Dilatometer Experiments	Gravity Beam Bending Experiments	Grain Growth Metallurgical Experiments

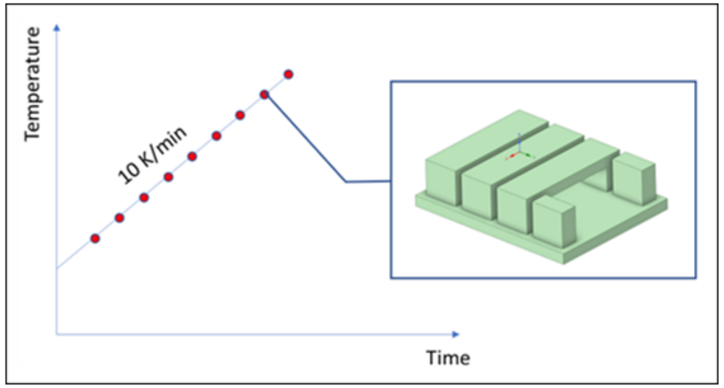
Observed Phenomenon →

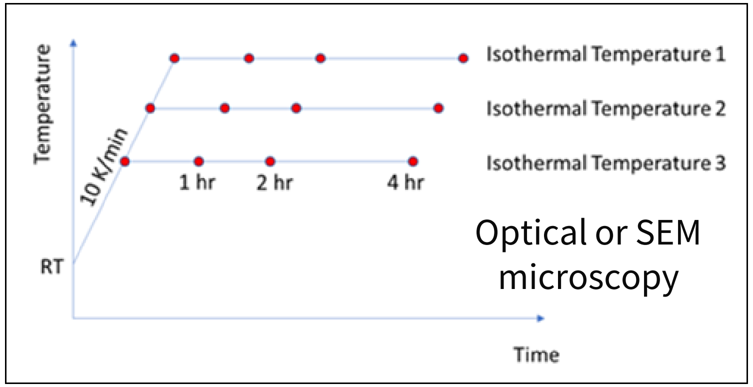
Parts which **do not have overhangs** susceptible to warping

Parts that are prone to **bending/warping during the sintering** process

Notice **differences in end densification** depending on the heating rate







Sintering Simulation Guide (ansys.com)

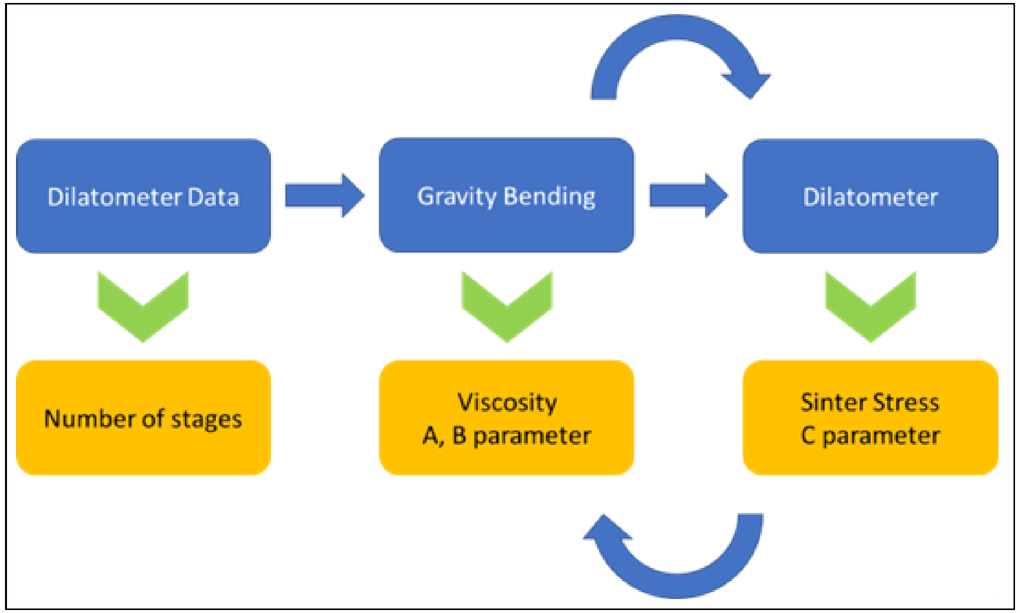
Sintering Calibration Guide (ansys.com)

Tutorial: Chapter 5: Workbench Additive Sintering Simulation - Printed Bridge (ansys.com)

Available sintering models in Ansys Additive Suite

Table 3.2: Sintering material model comparisons

Author(s)	Uniaxial Viscosity Model	Sintering Stress Model	Grain-Growth Model	Viscous Moduli Model
Paudel et al. [1]	**Grain-Size Corrected Arrhenius** $\eta = AT\exp\left(\frac{B}{T}\right)\cdot\left(\frac{g}{g_0}\right)^3$	**Olevsky** $\sigma_s = \frac{C\rho^2}{d_0}$	**Parabolic** $\dot{g} = \frac{1}{g} D\exp(-\frac{Q_g}{RT})$	**Riedel**
Song et al. [1]	**Grain-Size Corrected Arrhenius** $\eta = AT\exp\left(\frac{B}{T}\right)\cdot\left(\frac{g}{g_0}\right)^3$	**Olevsky** $\sigma_s = \frac{C\rho^2}{d_0}$	**Parabolic** $\dot{g} = \frac{1}{g} D\exp(-\frac{Q_g}{RT})$	**Riedel**
Zhang et al. [4]	**Arrhenius** $\eta = A\exp\left(\frac{B}{T}\right)$	**Grain-Size Corrected Olevsky** $\sigma_s = \frac{C\rho^2}{g}$	**Parabolic** $\dot{g} = \frac{1}{g} D\exp(-\frac{Q_g}{RT})$	**SOVS**



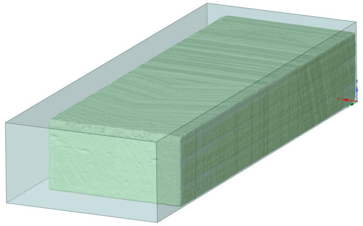
Calibrating new material

1. Song, J., Gelin, J. C., Barriere, T., & Liu, B. (n.d.). Experiments and numerical modelling of solid state sintering for 316L stainless steel components. *800* . https://doi.org/10.1016/j.jmatprotec.2006.04.111
2. Kerbart, G., Manière, C., Harnois, C., & Marinel, S. (n.d.). Predicting final stage sintering grain growth affected by porosity. https://arxiv.org/abs/2011.12402
3. Paudel, B. J, Conover, D., Lee, J., & To, A. C. A computational framework for modeling distortion during sintering of binder jet printed parts. *Journal of Micromechanics and Molecular Physics*. 6.4 (2021): 95-102.
4. Zhang, R. (2005). Numerical Simulation of Solid-State Sintering of Metal Powder Compact Dominated by Grain Boundary Diffusion. The Pennsylvania State University. https://etda.libraries.psu.edu/files/final_submissions/5423

Agenda

Case Study:

- Motivation
- Simulation Capabilities
- Theory Background
- Calibration



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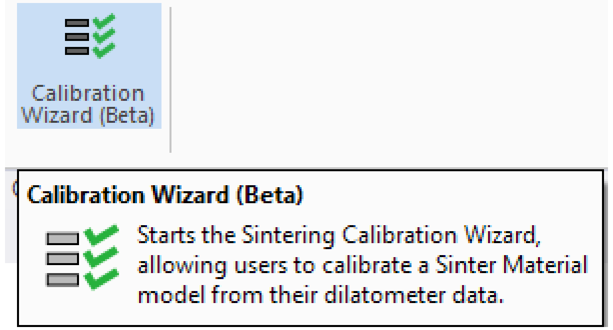
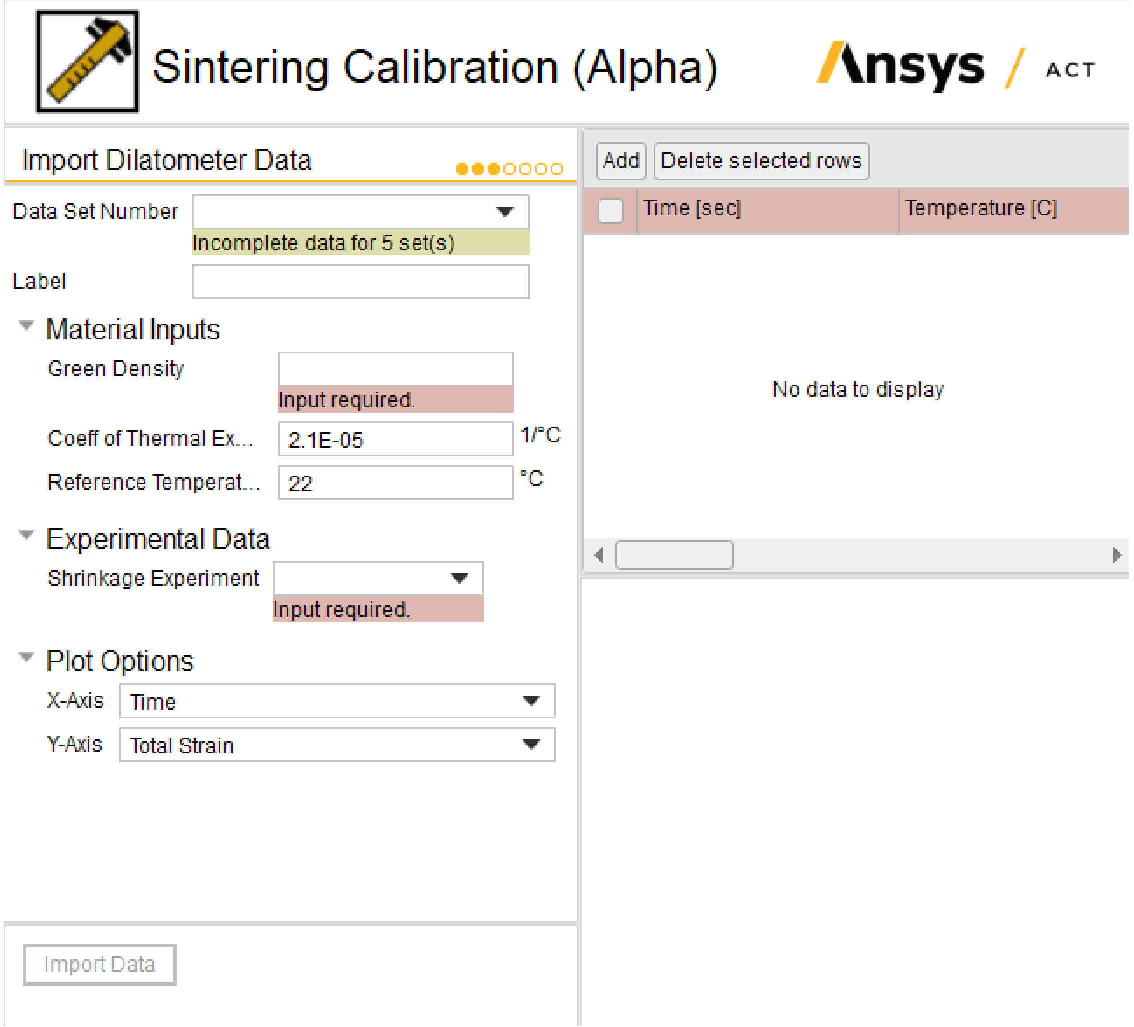
Ansys Mechanical Native Calibration Wizard (Beta)





Quick and easy way to calibrate sintering material model based on dilatometer tests data

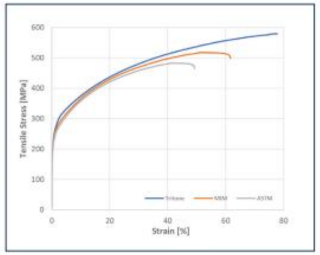
Tritone's 316L SS Material and Process Data

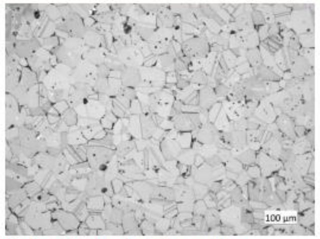
Material datasheet

316L Stainless Steel

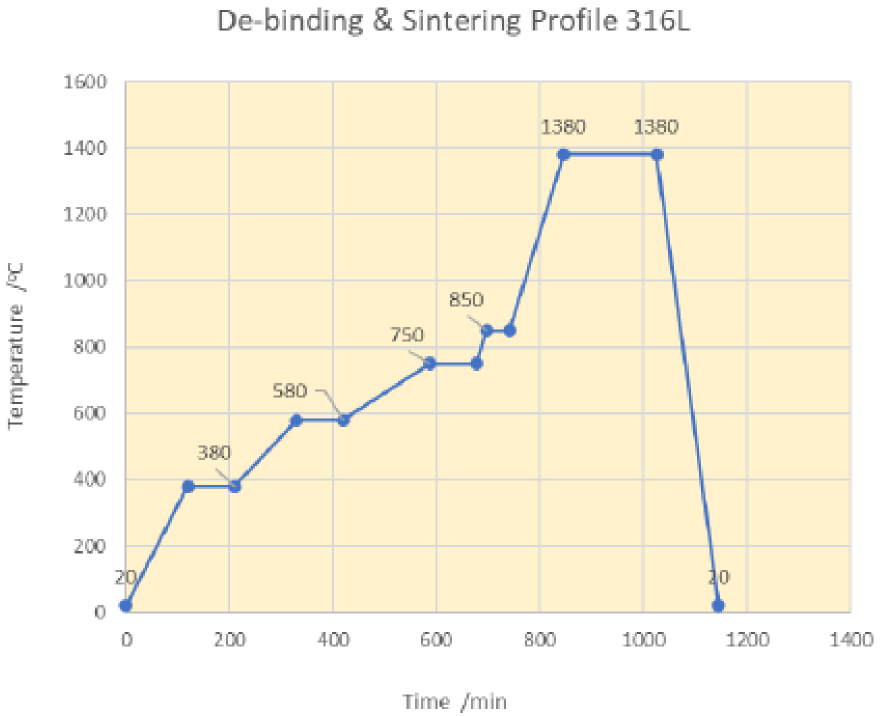
Composition – According to ASTM A276-06

Composition	Amount
Carbon	0.03%
Silicon	1.0%
Manganese	2.0%
Phosphorous	0.045%
Sulfur	0.03%
Chromium	16.0-18.0%
Nickel	10.0-14.0%
Molybdenum	4.08%
Iron	Bal.





Typical Mechanical Properties



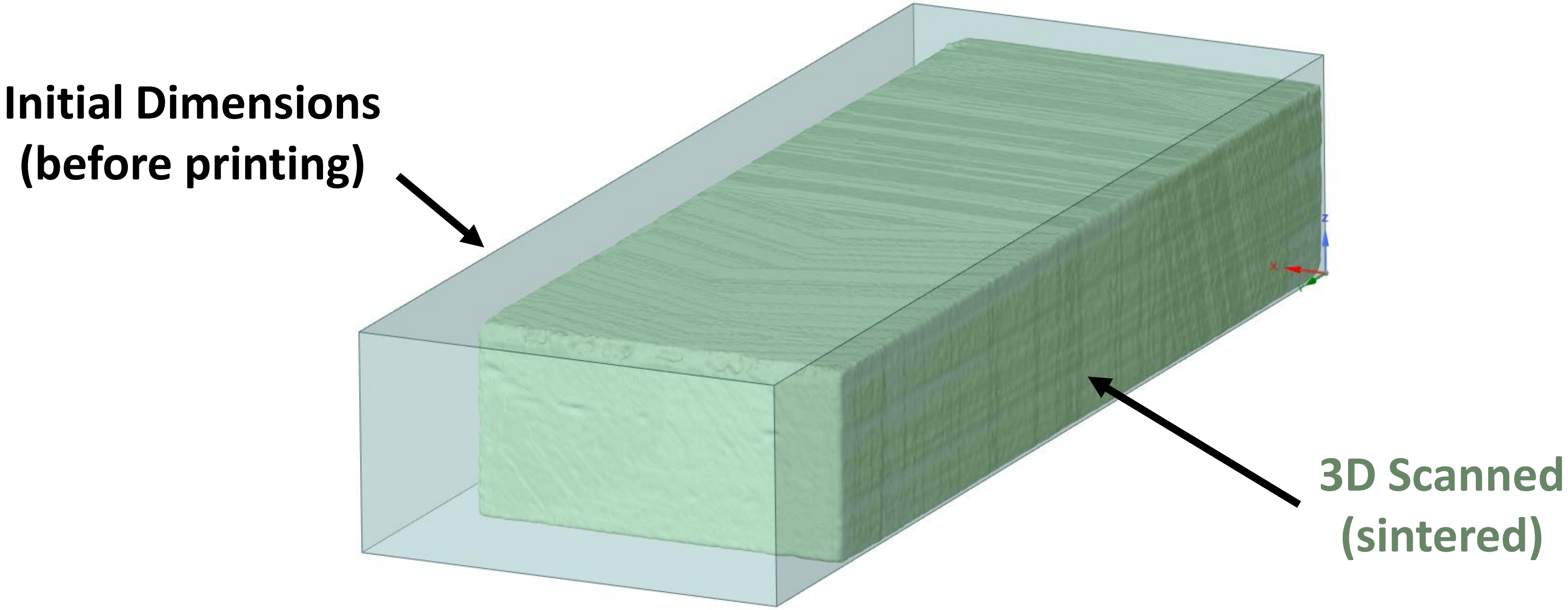
Typical Mechanical Properties

	Standard	Tritone	MIM MPIF-35 (typical)	Wrought ASTM A276
Ultimate Tensile Strength	ASTM E8	591 MPa	520 MPa	485 MPa
0.2% Yield Strength	ASTM E8	213 MPa	175 MPa	170 MPa
Elongation at Break	ASTM E8	>60%	50%	40%
Hardness	ASTM E18	67 HRB	67 HRB	-
Relative Density	ASTM B962	>99%	95%	100%

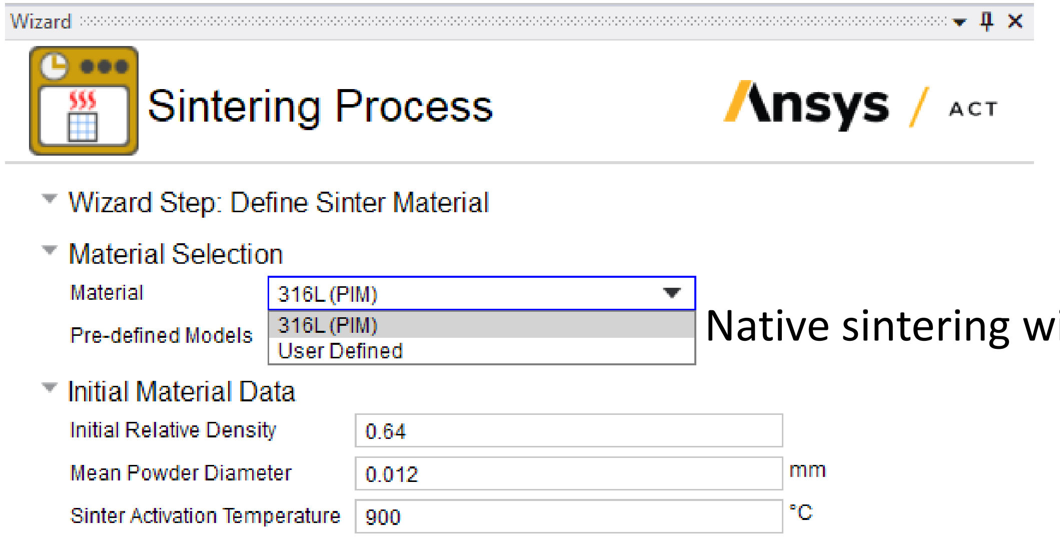
Mean Powder Diameter	μm	12
Green Density Ratio (compared to sintered)	-	0.64
Sintering Activation Temperature	℃	900

Calibration Beam Specimen

		Initial	Sintered
Thickness	mm	6.35	5.58
Width	mm	12.7	11.2
Length	mm	35	30.84

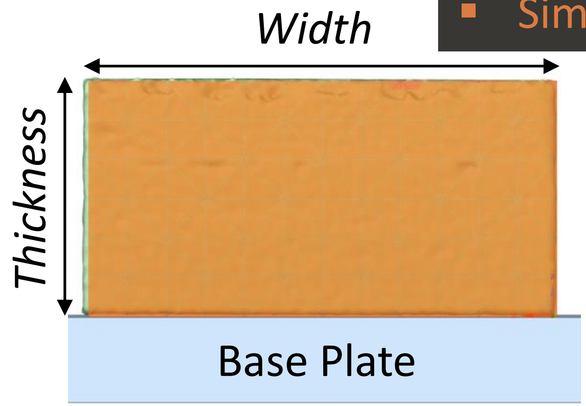


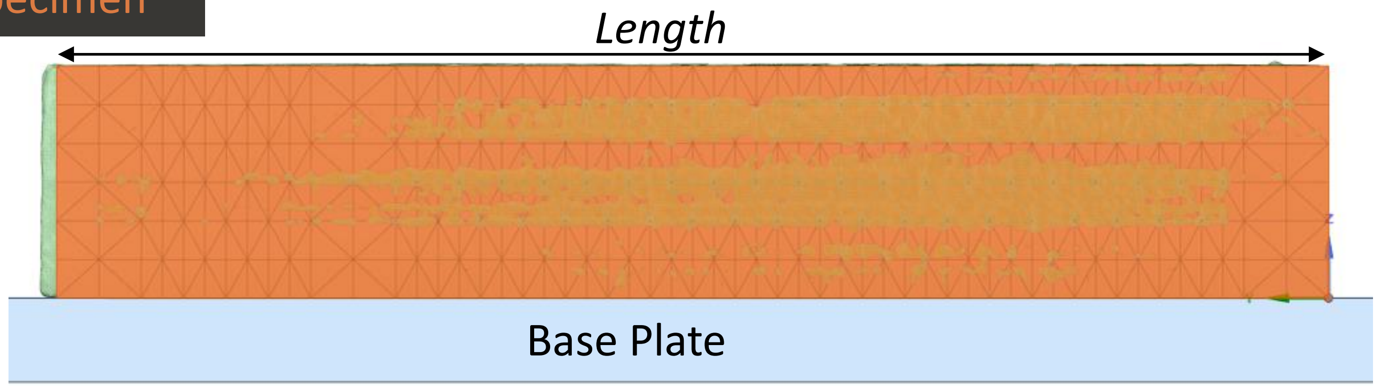
Uncalibrated Sintering Simulation



Native sintering wizard material

- 3D scanned sintered specimen
- Simulated sintered specimen





Model Calibration with OptiSlang

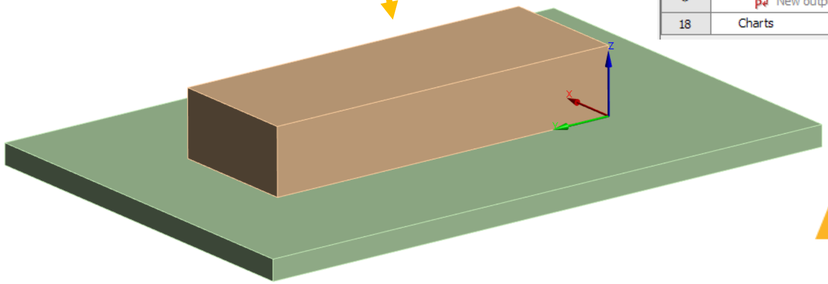
Material model input parameters

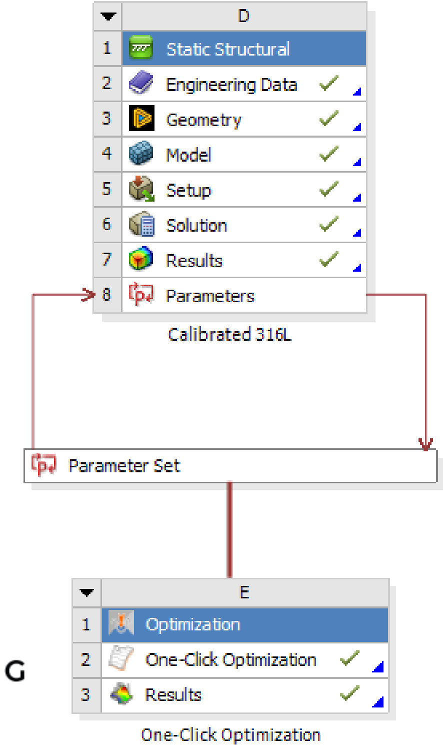
Details of "Sinter Material"	
Geometry	
Scoping Method	Geometry Selection
Geometry	1 Body
Sintering Model	
Material	User Defined
Material Label	Tritone316L
Initial State Data	
Green Density	0.64
Mean Powder Diameter	0.12 mm
Sintering Stress	
Activation Temperature	900 °C
Model	Olevsky (Grain-Size corrected)
Input by	Single Stage
P Pre-Factor	8.07952411477845 N/mm
Exponent	2
Uniaxial Viscosity	
Model	Arrhenius
Input by	Single Stage
P Pre-Factor	3.02746964404441 MPa·s
P Activation Energy	123966631.068764
Temperature Exponent	1
Grain Size Exponent	3
Grain Growth Kinetics	
Model	Parabolic
Initial Grain Size	0.006 mm
Input by	Single Stage
P Pre-Factor	6.63192815958552
P Activation Energy	9201441680.24426
Viscous Moduli	
Model	Riedel
Shear Moduli density Coefficient	1
Shear Moduli density Exponent	2
Bulk Moduli density Coefficient	1
Bulk Moduli density Exponent	2
Viscous Poissons coefficient	0.5
Anisotropy	
Anisotropic Factors	Tabular Data

Outline of All Parameters

	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	Input Parameters			
3	Calibrated 316L (D1)			
4	P6	Sinter Material Sintering Stress Pre-Factor	0.000696	N mm^-1
5	P7	Sinter Material Uniaxial Viscosity Pre-Factor	1.121E-06	MPa s
6	P8	Sinter Material Uniaxial Viscosity Activation Energy	1.6712E+08	
7	P9	Sinter Material Grain Growth Kinetics Pre -Factor	9.8E-07	
8	P10	Sinter Material Grain Growth Kinetics Activation Energy	3.158E+08	
*	New input parameter	New name	New expression	
10	Output Parameters			
11	Calibrated 316L (D1)			
12	P1	LOC_DEFZ Maximum	5.4474	mm
13	P2	LOC_DEFX Minimum	0.8236	mm
14	P3	LOC_DEFX 2 Maximum	11.876	mm
15	P4	LOC_DEFY Minimum	2.2963	mm
16	P5	LOC_DEFY 2 Maximum	32.704	mm
*	New output parameter		New expression	
18	Charts			

Final simulated dimensions as output parameters





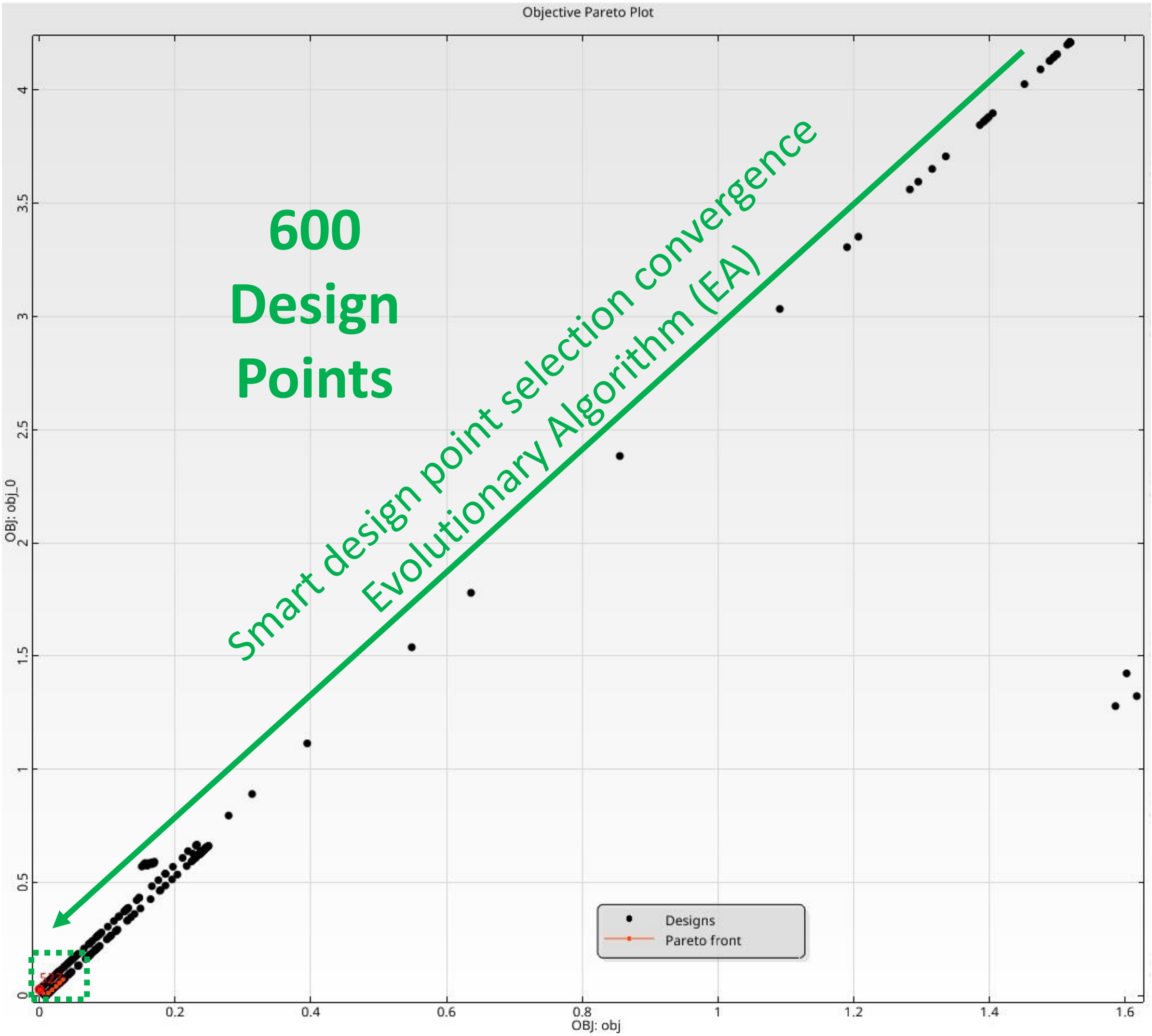
Ansys / OPTISLANG

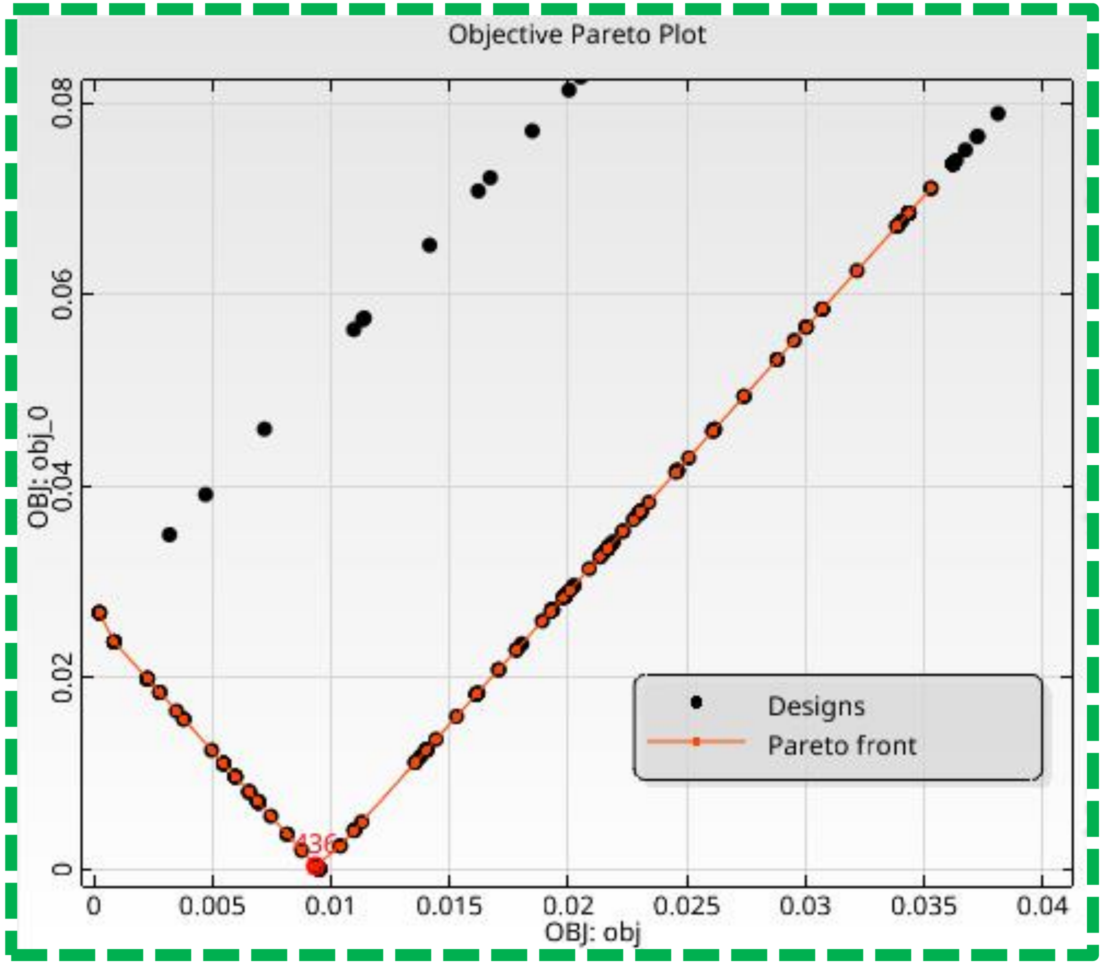
Criteria

Name	Type	Expression	Criterion	Evaluated expression
Length	Objective	abs(30.84-(LOC_DEFY_2_Maximum-LOC_DEFY_Minimum))	MIN	0.432686
Width	Objective	abs(11.2-(LOC_DEFX_2_Maximum-LOC_DEFX_Minimum))	MIN	0.147203
Thickness	Objective	abs(5.58-LOC_DEFZ_Maximum)	MIN	0.132628

Parametric Optimization with optiSLang

Tritone Industrial Additive Manufacturing

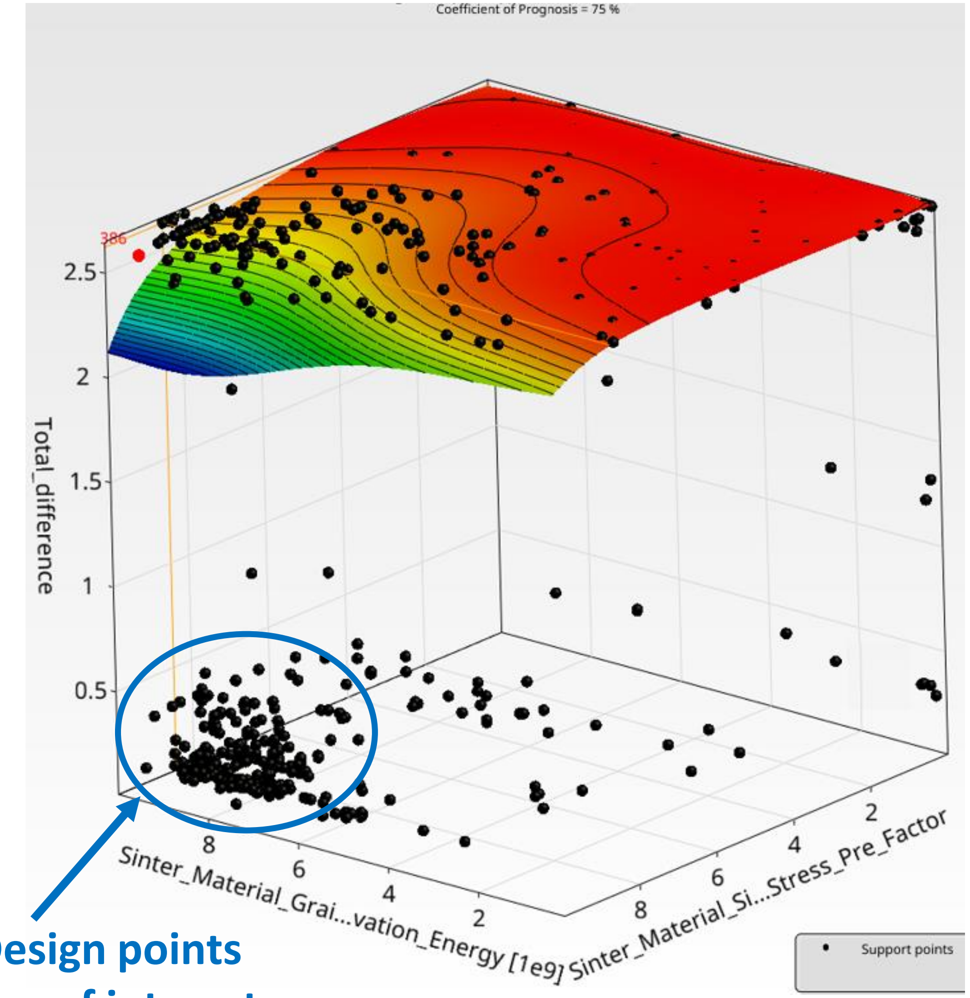




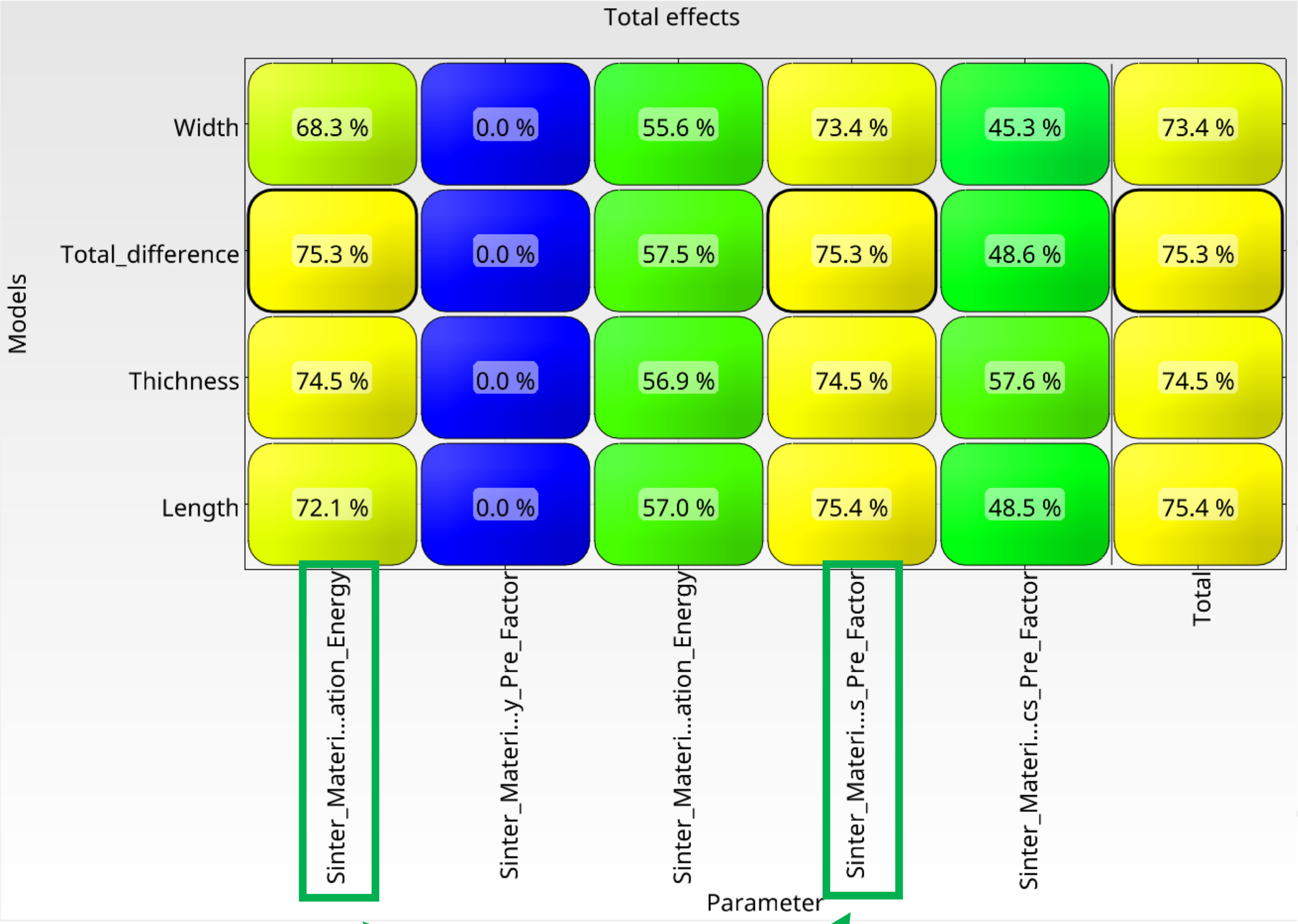
Ansys

Ansys / OPTISLANG

Sensitivity Analysis with optiSLang

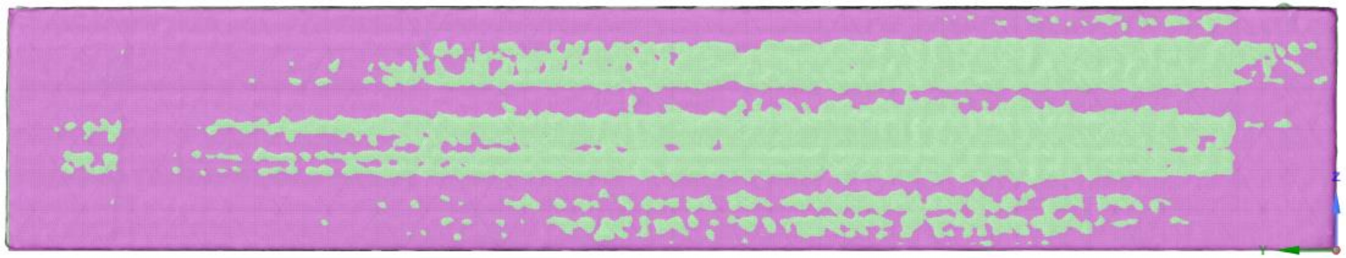


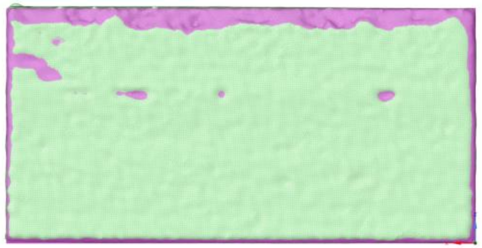
Design points area of interest



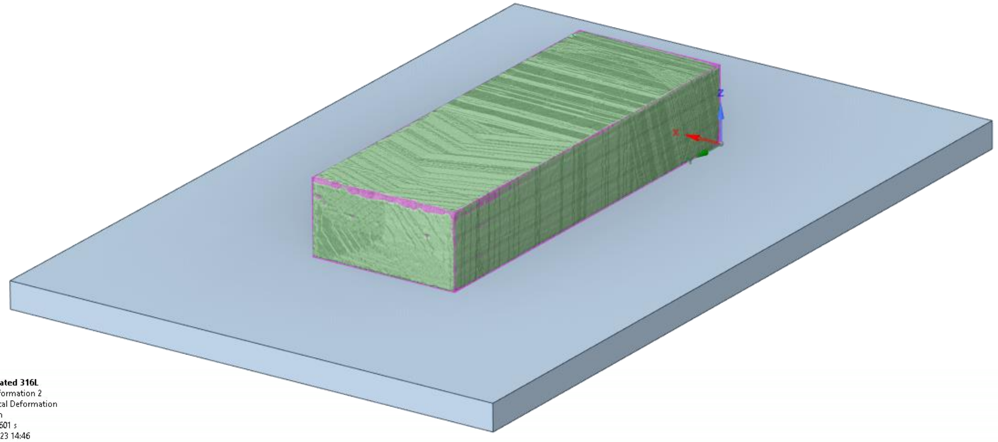
Most Significant parameters

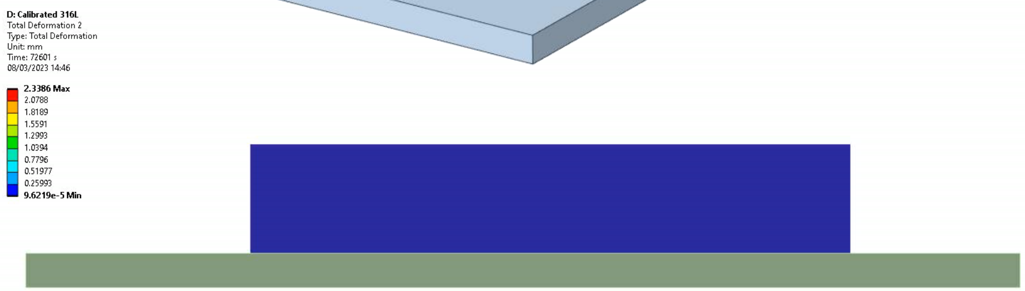
Best Design Point (DP 538)





- 3D scanned sintered specimen
- Simulated sintered specimen





Agenda

- Motivation
- Simulation Capabilities
- Theory Background
- Calibration

Case Study:

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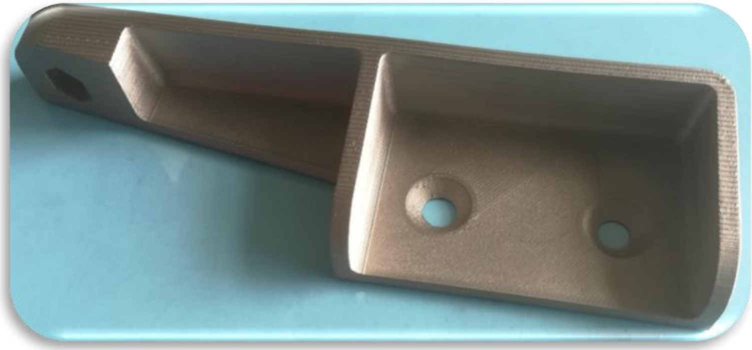

- Sintering Simulation
- Distorsion Compensation Analysis
- Verification – Sintering Simulation of Distorted Part
- Validation- Sintering Printed Distorted Part

Case Study- Initial Sintered Result

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316L Stainless Steel 3D Printed Door Stopper

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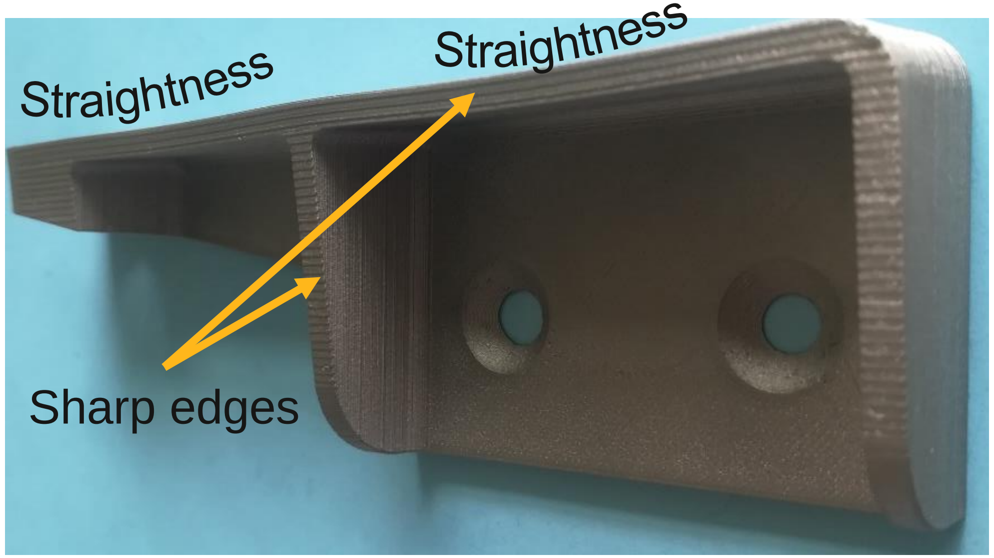
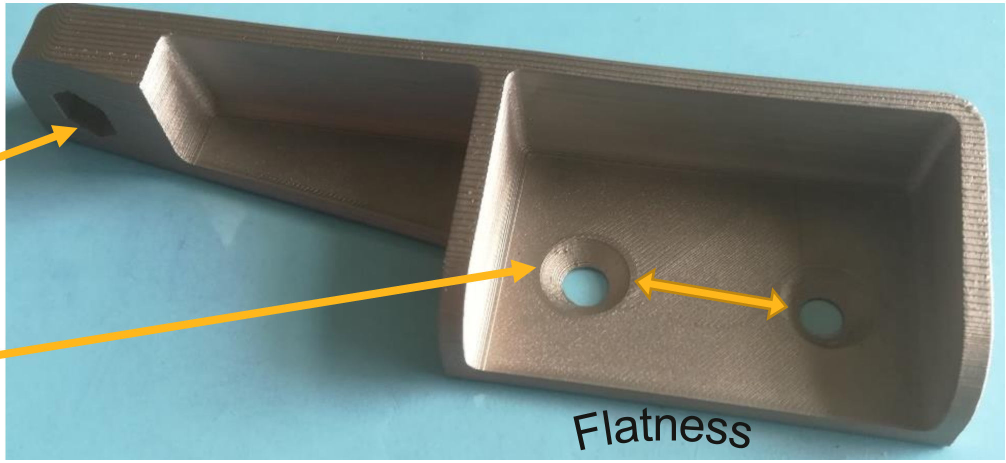


M5/SW8 nut fit

Holes Distance:
Specified: 30 mm,
Measured 29 mm



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Flat Orientation Sintering Simulation (15% scaled model)

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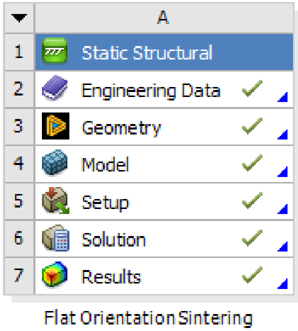
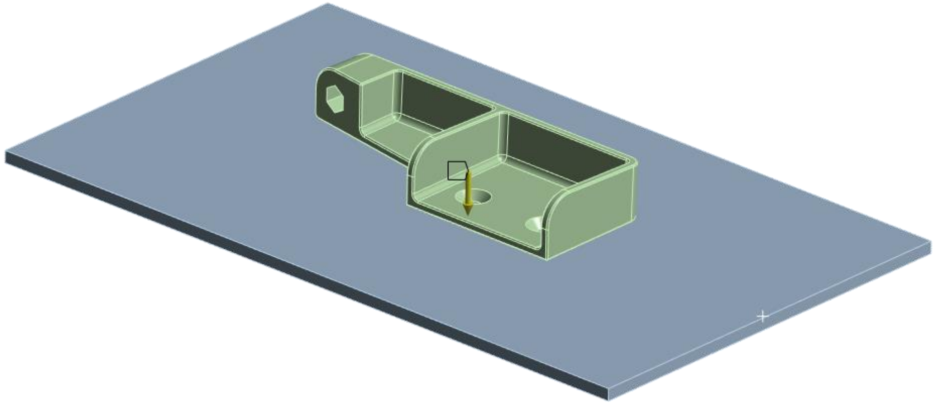
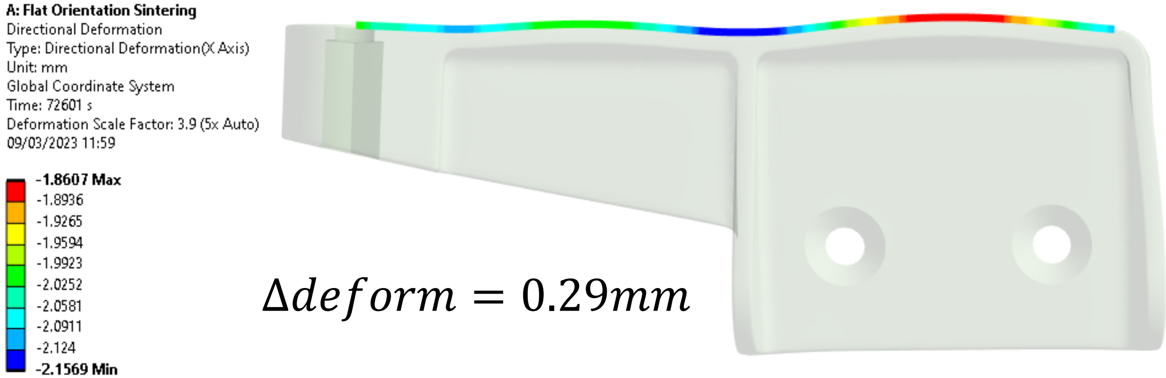
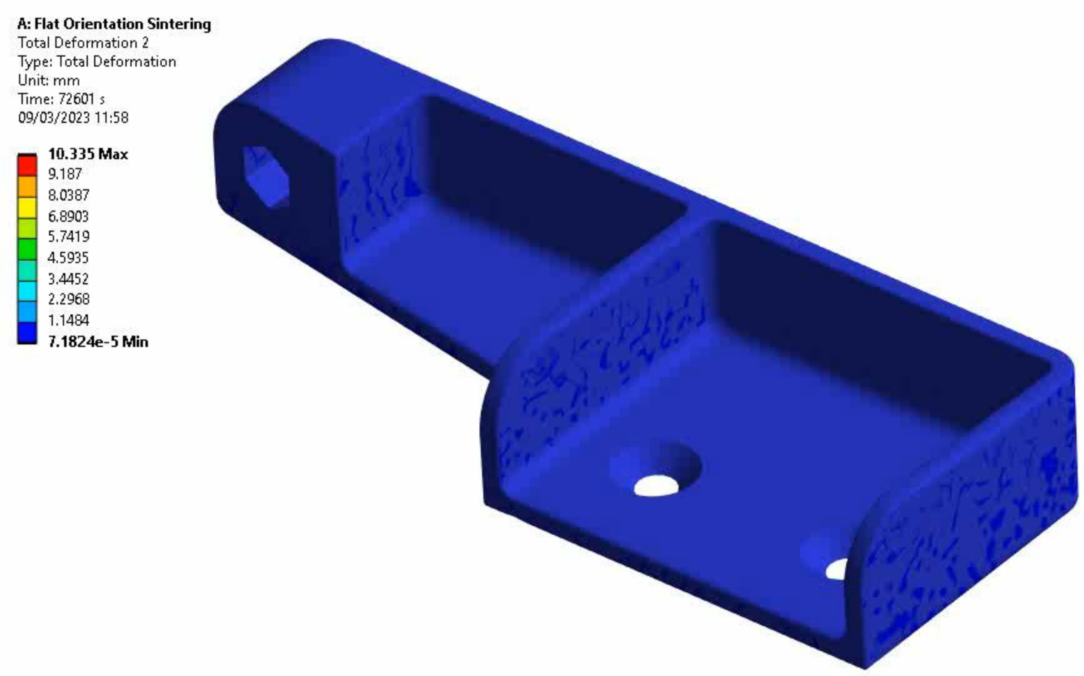






$$\Delta deform = 0.29mm$$



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Tilted Orientation Sintering Simulation (15% scaled model)

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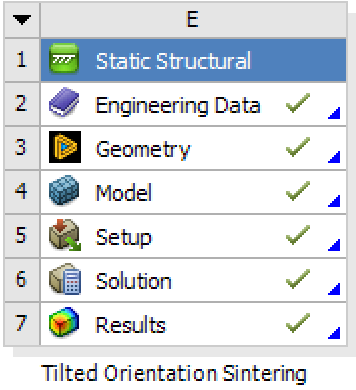
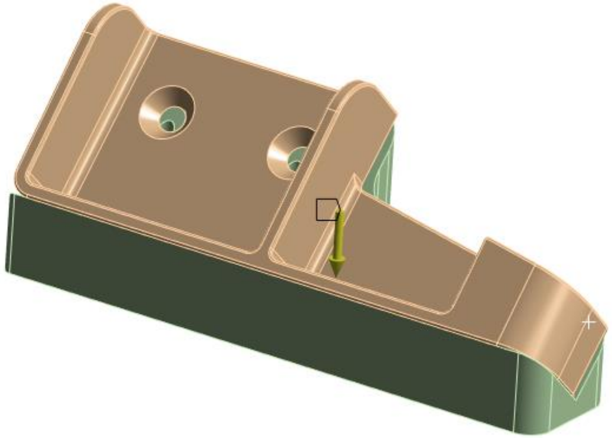
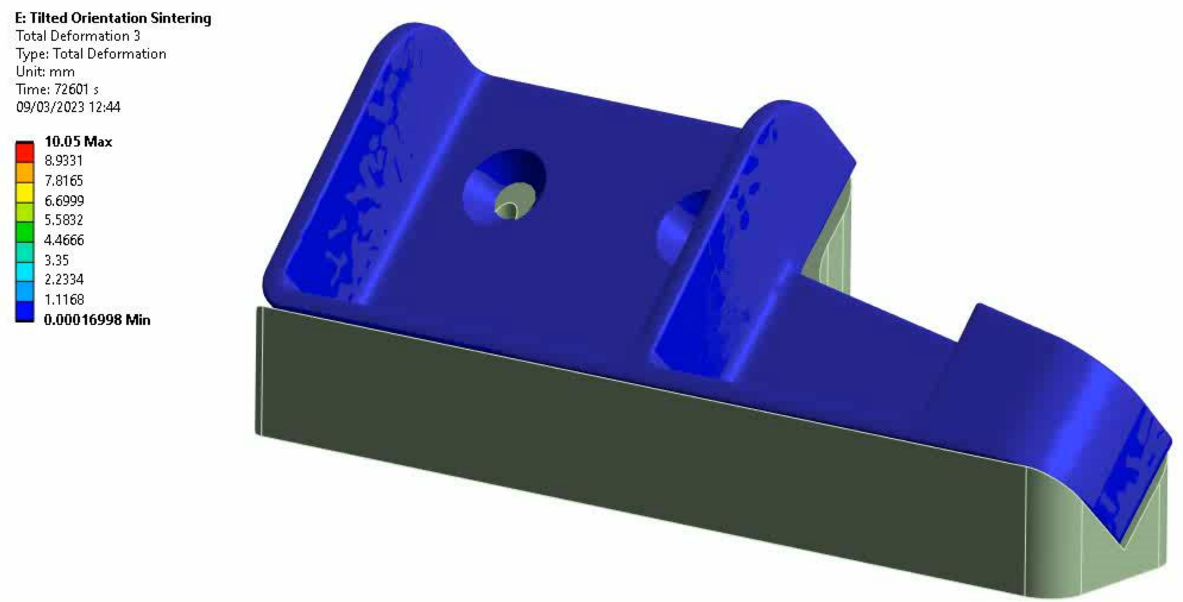
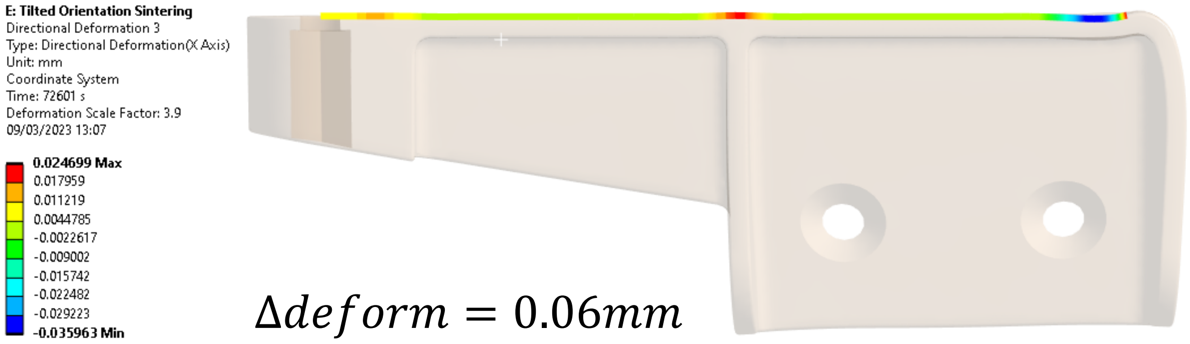
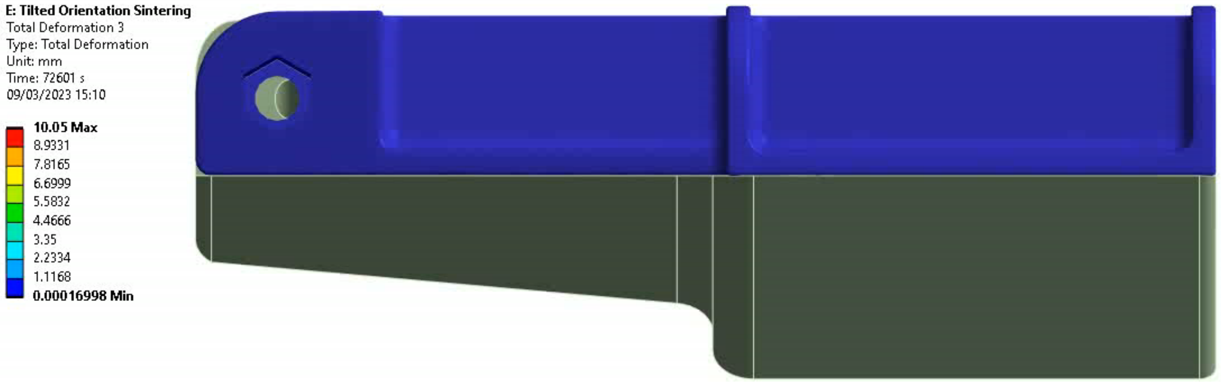








$$\Delta deform = 0.06mm$$



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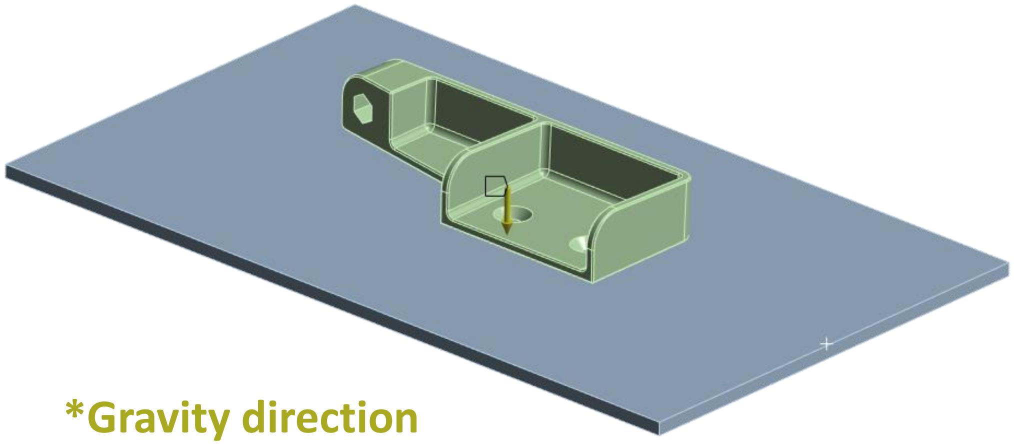
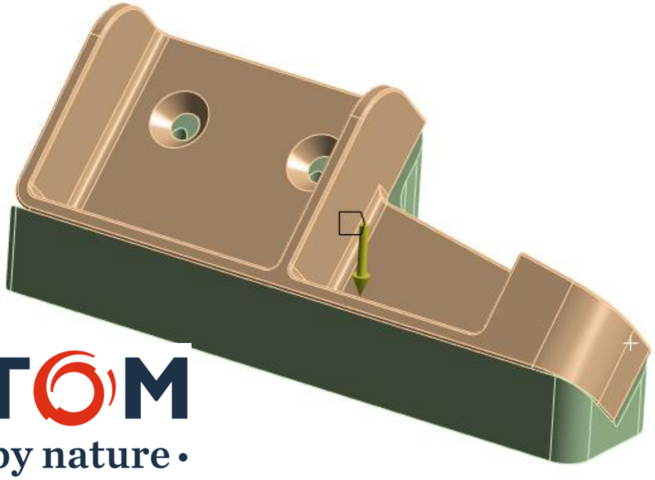
Capturing Gravity Influence



*Gravity direction



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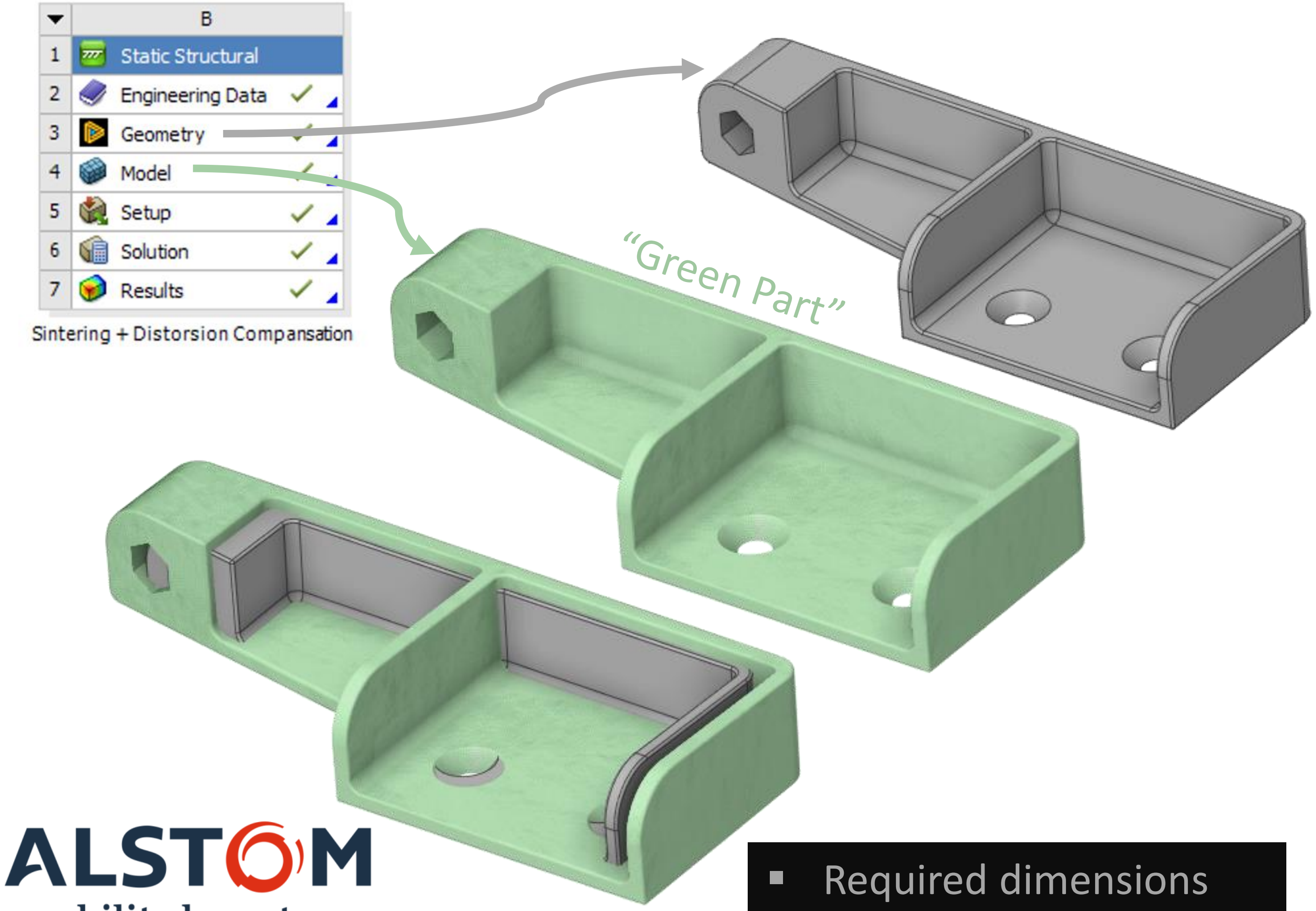
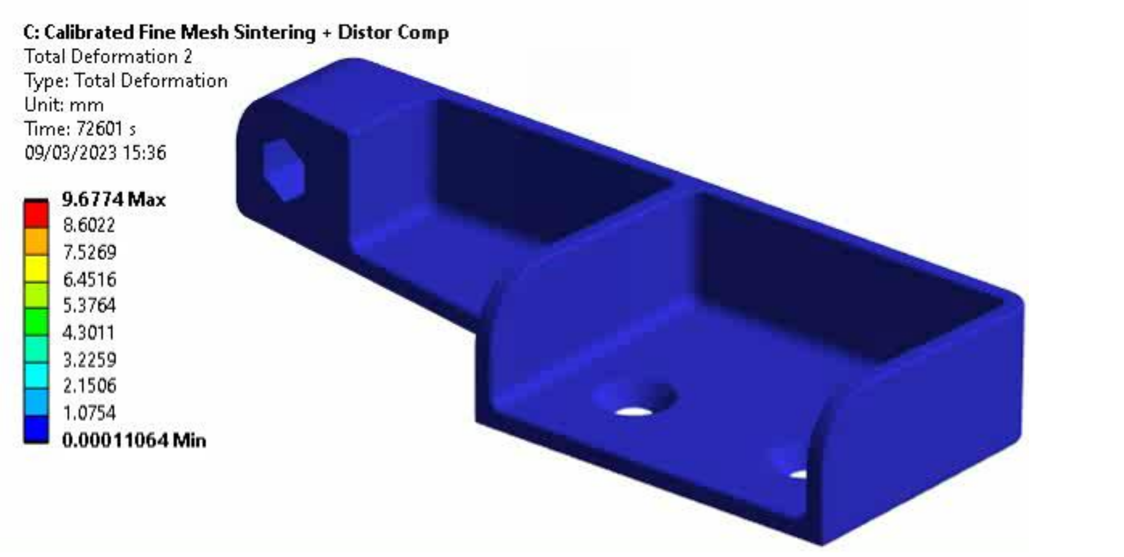
Flat Orientation Distortion Compensation Analysis





- Required dimensions
- Distorted compensated

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Verification – Sintering Simulation of Distorted Part

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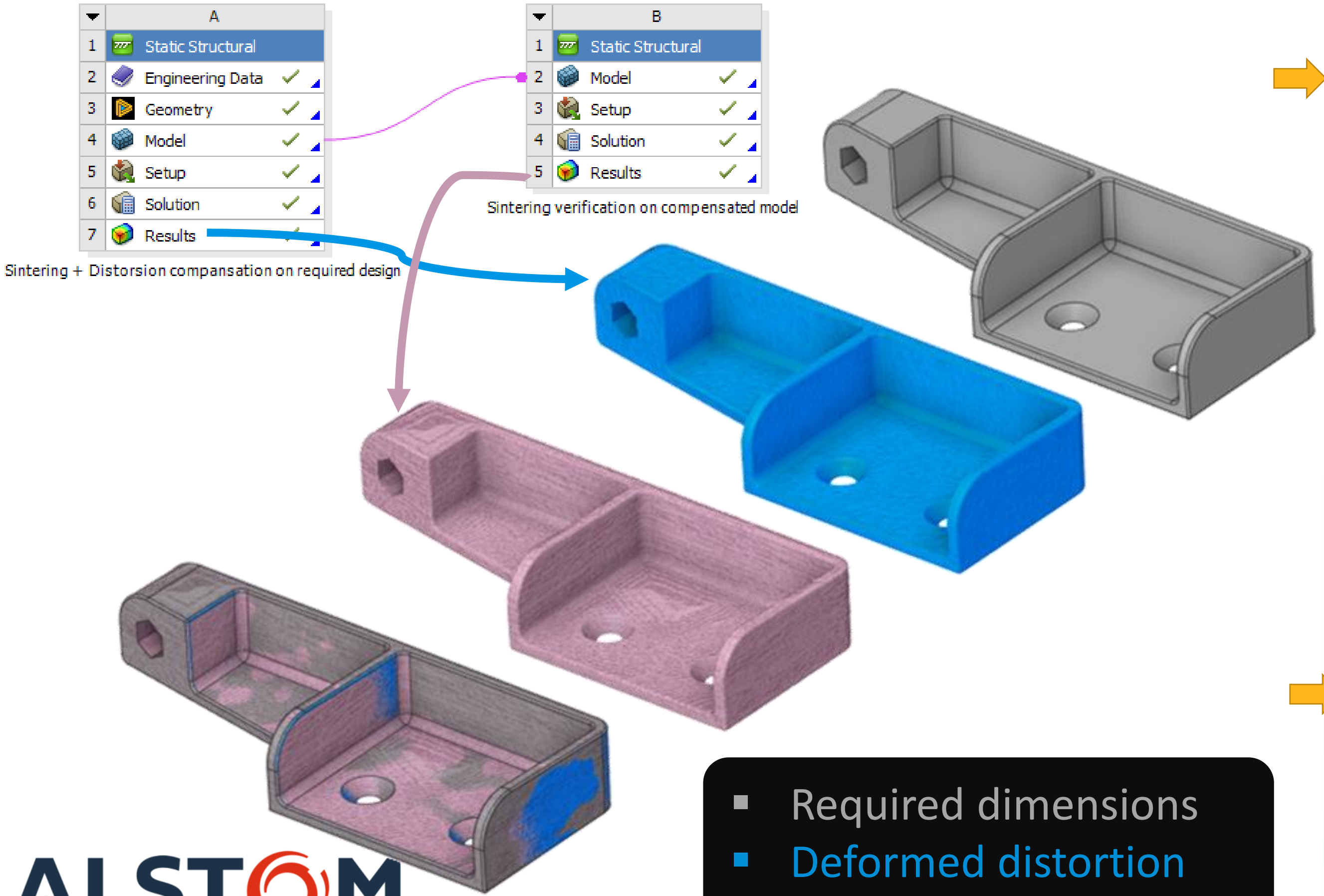
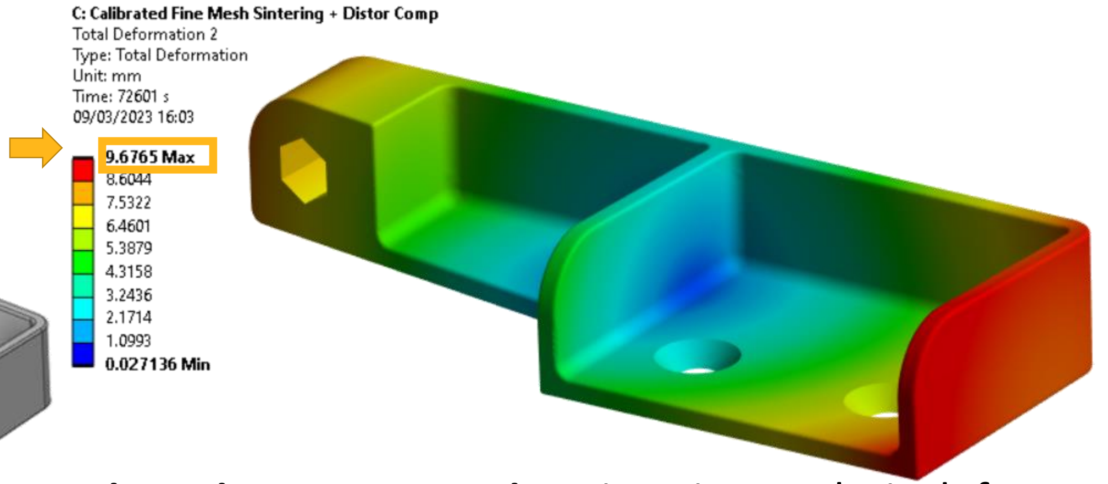
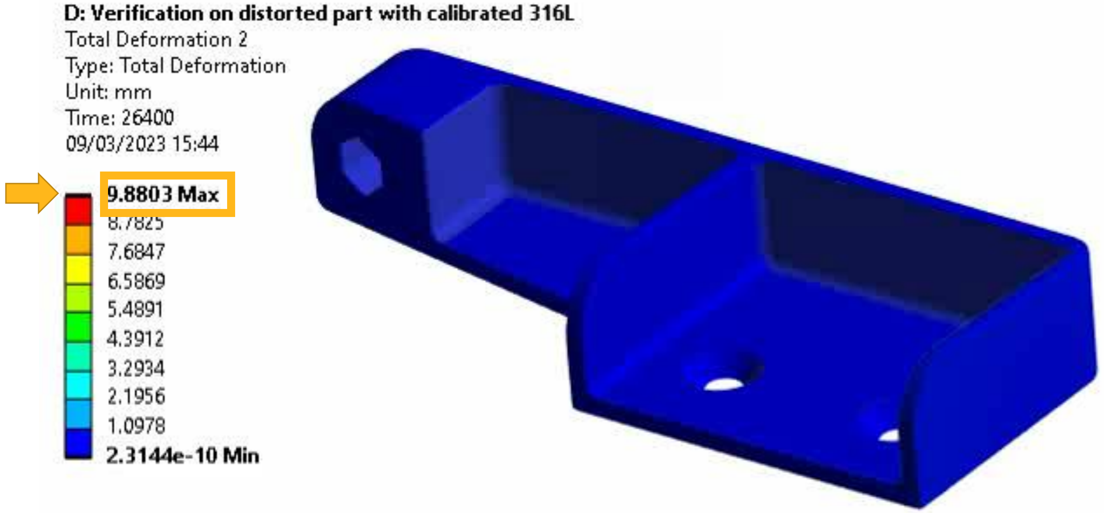




Distorsion compensation sintering analysis deformation



Verification - Distorted sintering analysis deformation

- Required dimensions
- Deformed distortion compensation
- Deformed verification

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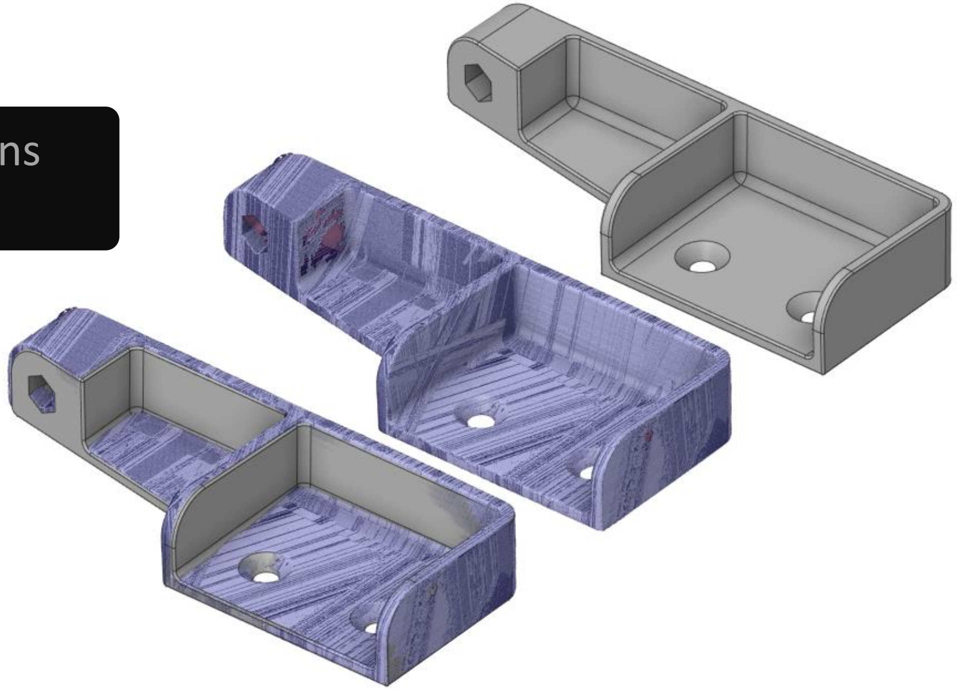
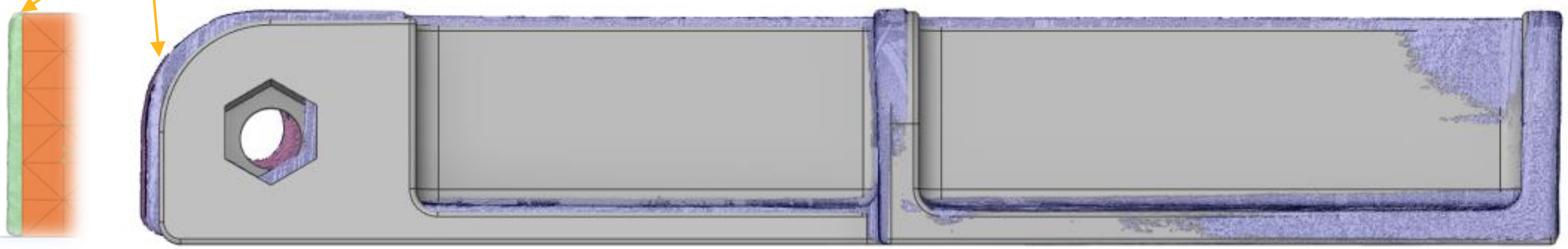
Validation- Sintering Printed Distorted Part (*Uncalibrated*)

Sintered part

- Required dimensions
- 3D Scanned



Similar distortions as uncalibrated specimen



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Summary

- Using **FEA** to simulate the sintering process is crucial to design and **predict desired dimensions and residual stress.**
- **Distorsion compensation** analysis can be used to create **precise initial part dimensions** before sintering and **avoid** the use of **supports**.
- **Material model calibration** is crucial due to **ingredients difference**.

Future work:

- Compare case study calibrated result
- Calibrate additional of Tritone's materials
- Using the new native sintering calibration tool in Ansys Mechanical
- Material calibrations based on advance methods.

Thank you for listening