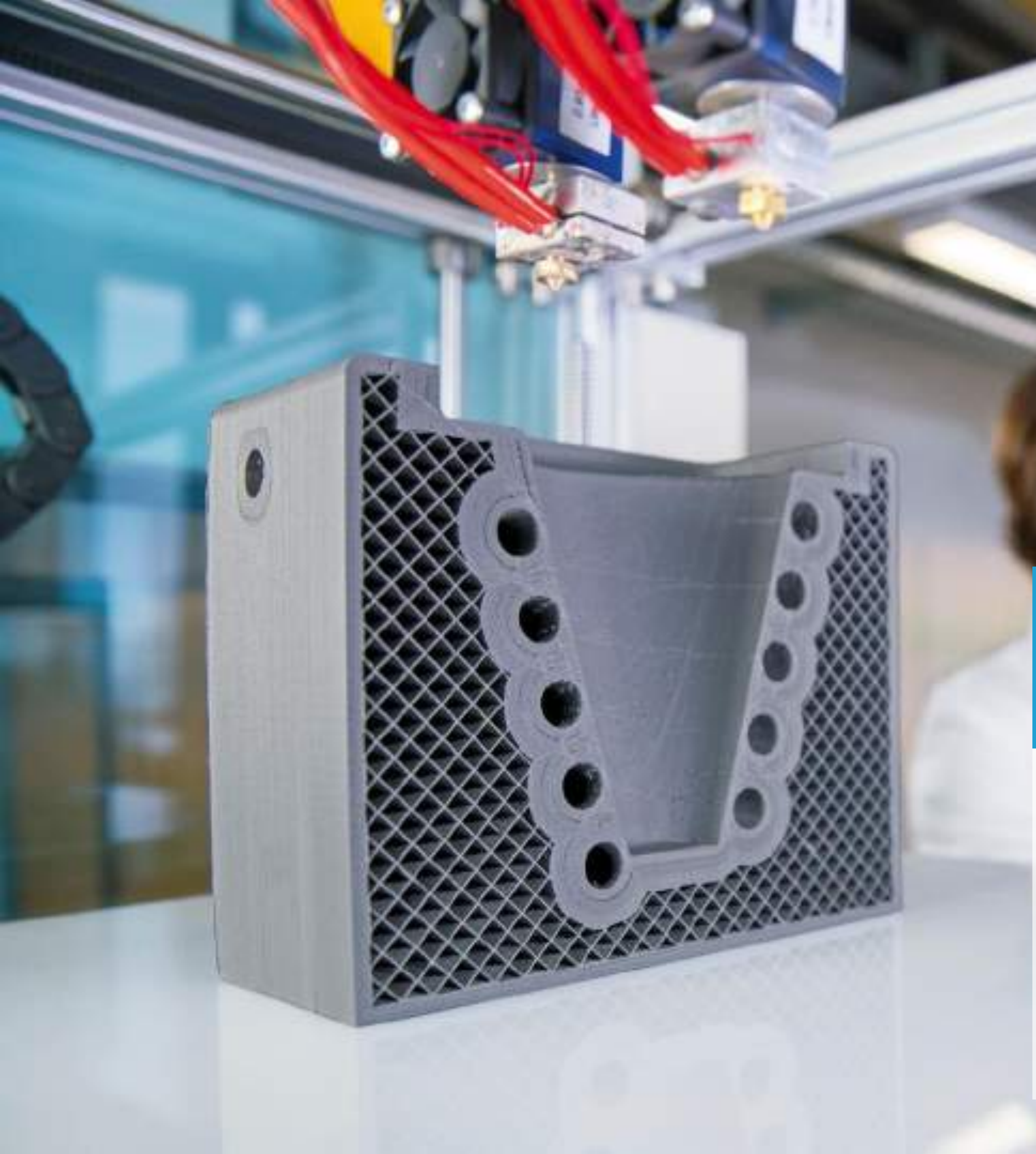

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Innovating Additive Manufacturing

Forward AM

Metals Systems In-House Training

James Pitts

Heidelberg – Q1, 2020

FORWARD AM
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Presentation Summary

- Introduction to BASF Forward AM
- Metal Fused Filament Fabrication Introduction & Process Workflow
- Debinding & Sintering (D&S) processes and equipment
- Ultrafuse 316L Design Guidelines
- Simulation
- Printer, Slicing, & Print Perpetration
- Printer Calibration
- Benchmark Protocol

BASF Group

- BASF’s chemistry is used in almost all industries
- Combining economic success, social responsibility, and environmental protection

Sales 2018	**€ 62,675 billion**
EBIT 2018	**€ 6,033 billion**
Employees 2018	**>122,000**
R&D is a major growth driver	**>11,000 employees worldwide**

Forward AM

- Established September 2017
- Headquartered in Heidelberg, Germany
- Superior materials & solutions for Additive Manufacturing (AM)
- Team of over 150 people dedicated to Additive Manufacturing
- Our Application Technology Center (ATC) sets the highest focus on customer applications

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What makes Forward AM unique

Experience

- Decades of BASF research on 3D Printing materials

Know-how

- Access to focused applications and industry
- Access to BASF Group material portfolio

Uniqueness

- One-stop shop for all AM technologies
- Largest portfolio of different 3D Printing materials

BASF 3DPS: Offerings At A Glance

Powder Bed Fusion (PBF)

PA6-based (MF, FR)

PA6-based low-melt (LM)

TPU powders

ADVANC3D Materials

PA11, PP, TPU (acquisition of Advanc3D)

Additive Extrusion Solutions (AES)

Filaments for industrial application

Filaments for desktop printing (acquisition of Innofil3D)

ESSENTIUM

Flash-fuse tech (Co-operation with Essentium)

Plastics for extrusion and big area 3D-P

Metal filaments

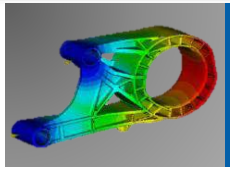
Liquid Formulations and Systems (LFS)

Photopolymers for SLA and DLP

Ceramic photopolymers

Photo-Resin for PPJ

Services and Solutions



Design and Simulation

Finishing and coating

Parts and services

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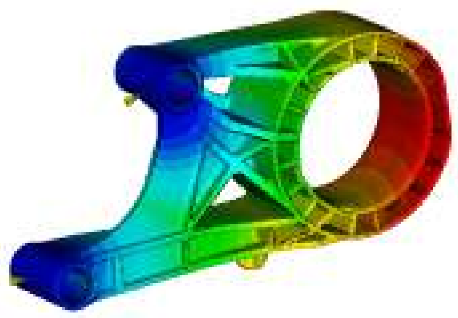
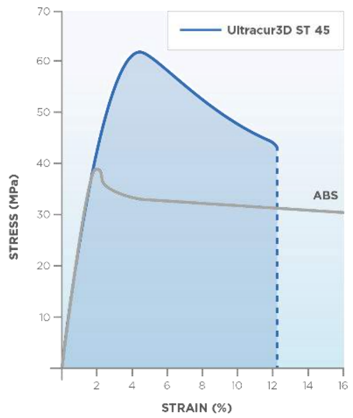
Our Mission: “Enable our customers to shape the Additive Manufacturing industrial revolution.”





Virtual Engineering

- Design
- Process Simulation
- Material Modeling
- Build Optimization

Benchmark Printing

- Technology Choice
- Material Choice
- Parameter Fine Tuning

Testing and Evaluation

- Mechanical
- Environmental
- Defining Standards
- Market / Application specific

Finishing and Post Processing

- Surface Characterization
- Mechanical, chemical treatment
- Coatings

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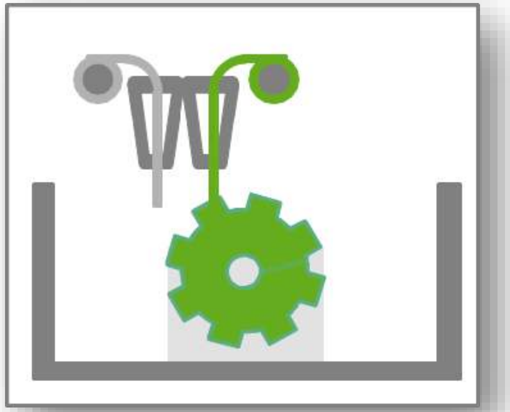
Introduction & Process Workflow
Metal Fused Filament Fabrication (MF³)

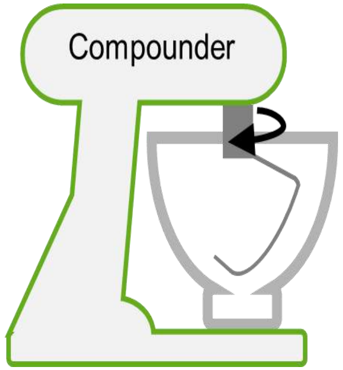
Process Workflow: Summary



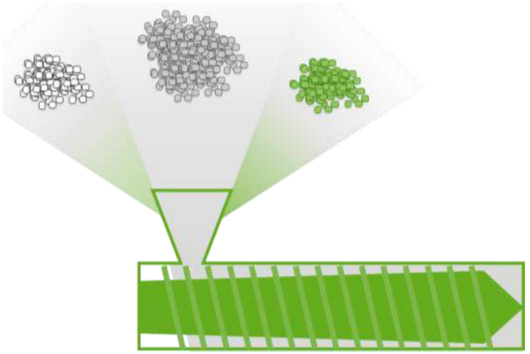
- **Metal Fused Filament Fabrication (MF³)**
  - Metal powder is combined with a binder to create a filament suitable for printing on most direct-drive and Bowden 3D printers
  - After printing, a debinding & sintering process results in a full metal part
- **Unique Value Propositions**
  - Low relative printer cost
  - Creation of hollow structures without the need for powder removal
  - Multi-material printing via dual extrusion equipped printers

Process Workflow: Feedstock Formulation

- **Metal Powders & Binders Are Combined To Produce Granulated Feedstocks**
  - Developed for Metal Injection Molding (MIM) feedstock production
  - MIM is nearly identical to plastic injection molding process
- **BASF Provides More Than 30 Years Of MIM Feedstock Experience**
  - Scalability; batch to serial production scale
  - Customizable material properties
  - Extensive quality control



Batch Process



Continuous Production

Granulate Feedstock

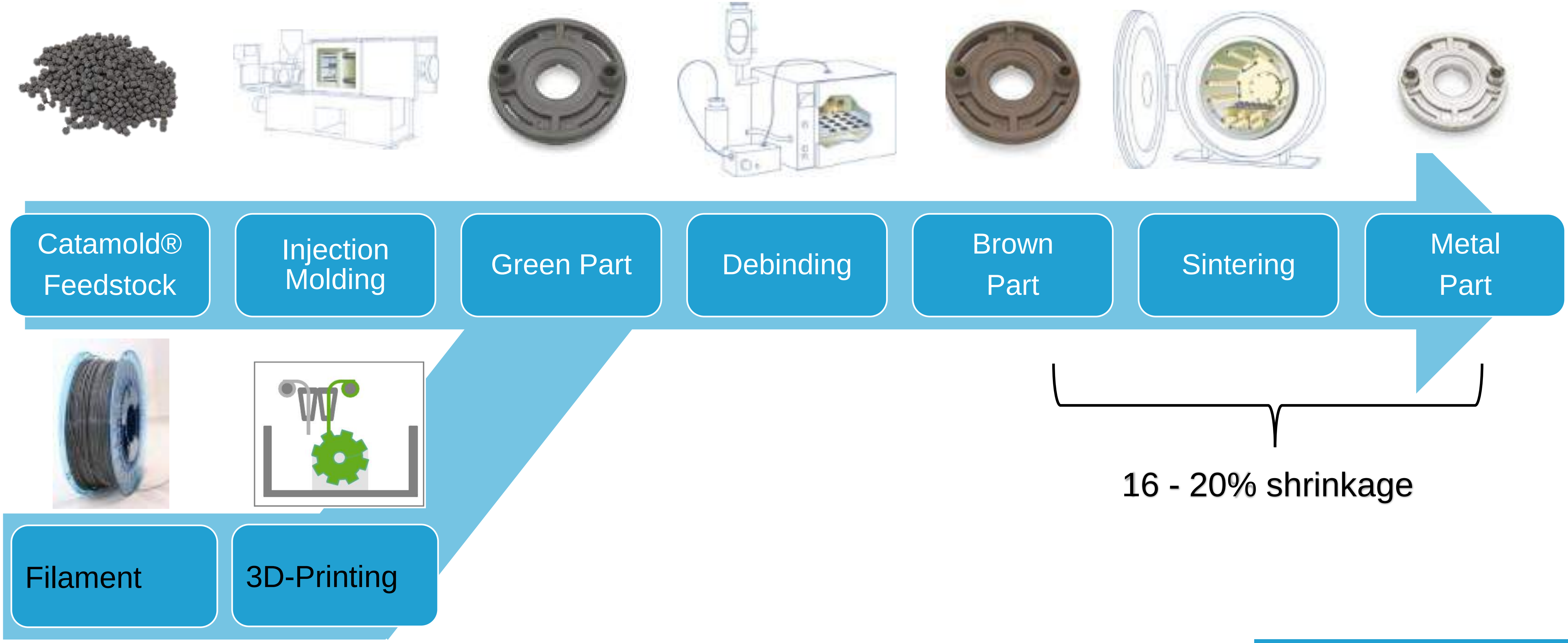
Process Workflow: MIM Compatibility

- **MIM Enables:**
  - High precision & industrial scale throughput
  - Cost advantages for large part numbers with tight tolerances
  - Complex & intricate metal parts
- **Applications**
  - Consumer & Sporting Goods
  - Automotive
  - Electronic
  - Medical

Process Workflow: MIM Compatibility

- **Disadvantages:**
  - High initial cost can prevent small series production
  - Long lead-times often required for new injection mold manufacture and testing
- **Additive as Disrupter & Force Multiplier:**
  - Specially adapted feedstocks are combined and filamentized to produce Ultrafuse 316L
  - Hybridize for first to market advantage; initial series with FFF while molds are being created
  - No mold required / no lead time to printing
  - Seamless integration of feedstock material in MIM process flow

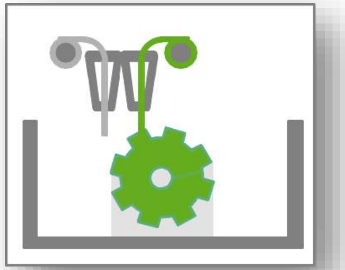
Process Workflow: Feedstock to Part



Introduction & Process Workflow

Debinding & Sintering (D&S) processes and equipment

Catalytic Debinding & Sintering Workflow



Printing → **Debinding** → **Sintering**

Volume shrinkage (16-20%)

"Green Part"

"Brown Part"

"Sintered Part"

Catalytic Debinding: “Green to Brown”

“Green Part”

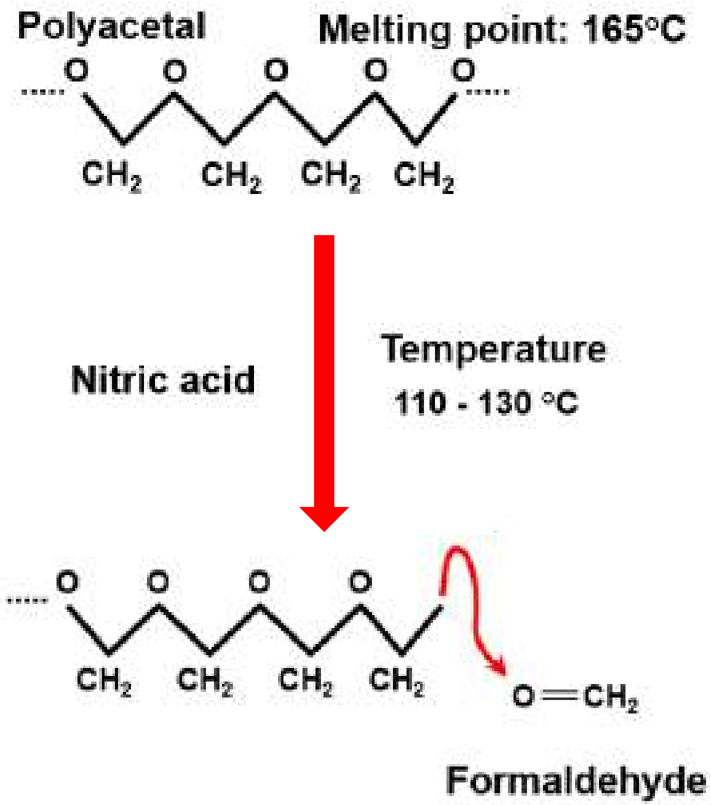
“Brown Part”

- **Material:** Powder + Binders
  - The metal powder in Ultrafuse 316L is held together using binding agents
  - The main binders are Polyacetal (POM) and a Polyolefin (backbone)
  - Before Ultrafuse 316L can be sintered, the POM binder must be removed
- **Catalytic Debinding:** The process of binder removal via a catalytic acid vapor (HNO3)
  - Catalytic debinding is an order of magnitude faster than thermal and solvent methods
  - Thermal and solvent debinding systems are not suited to POM-based feedstocks

Catalytic Debinding: A Chemical Process

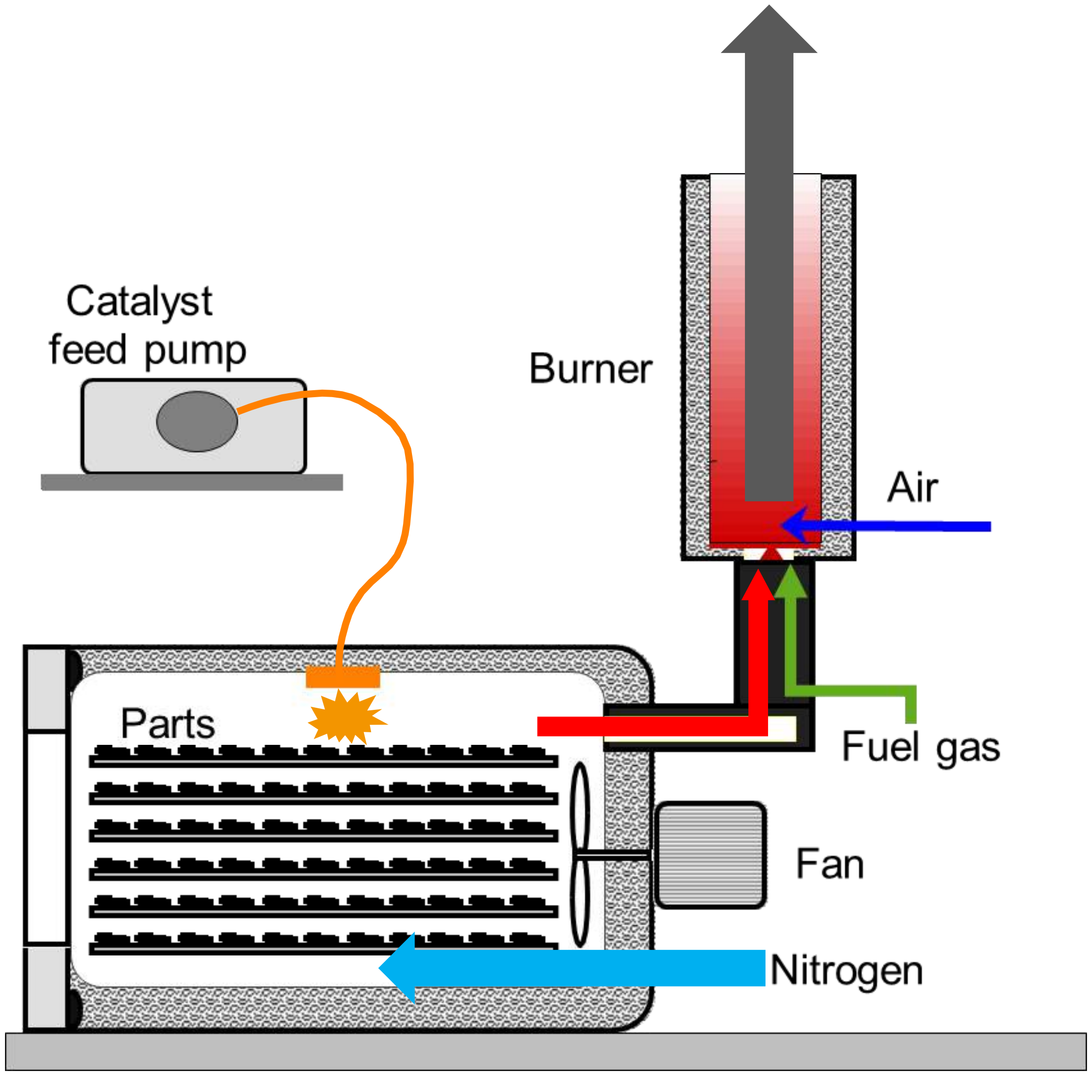
Catalytic Process

- POM decays into formaldehyde gas in an acidic atmosphere
- Decomposition below POM’s melting point, maintains part shape
- Reaction proceeds rapidly from outside in (1 - 2 mm/h)
  - The thicker the part the longer the debinding time required
  - Faster and cleaner than thermal and solvent methods



Catalytic Debinding: Process Example

- **Part sizes and loading**
  - Defined by oven size and type
- **Process**
  - Nitrogen is added to prevent combustion
  - Gaseous nitric acid is added
  - The resulting formaldehyde is burned off
  - Combustion gases are vented away



Catalytic Debinding: Equipment

- **Catalytic Debinding Ovens**
  - Modern catalytic debinding ovens are highly automated
    - Increased process stability
    - Ensure safe operation
- **Mass loss (>10.5%) – 12.5% Final Mass Reduction**
  - Catalytic debinding removes 90% of organic binders (POM)
  - Secondary backbone is kept to support brown parts during transfer to sintering

Source: www.nabertherm.com

Sintering: “Brown to Sintered”

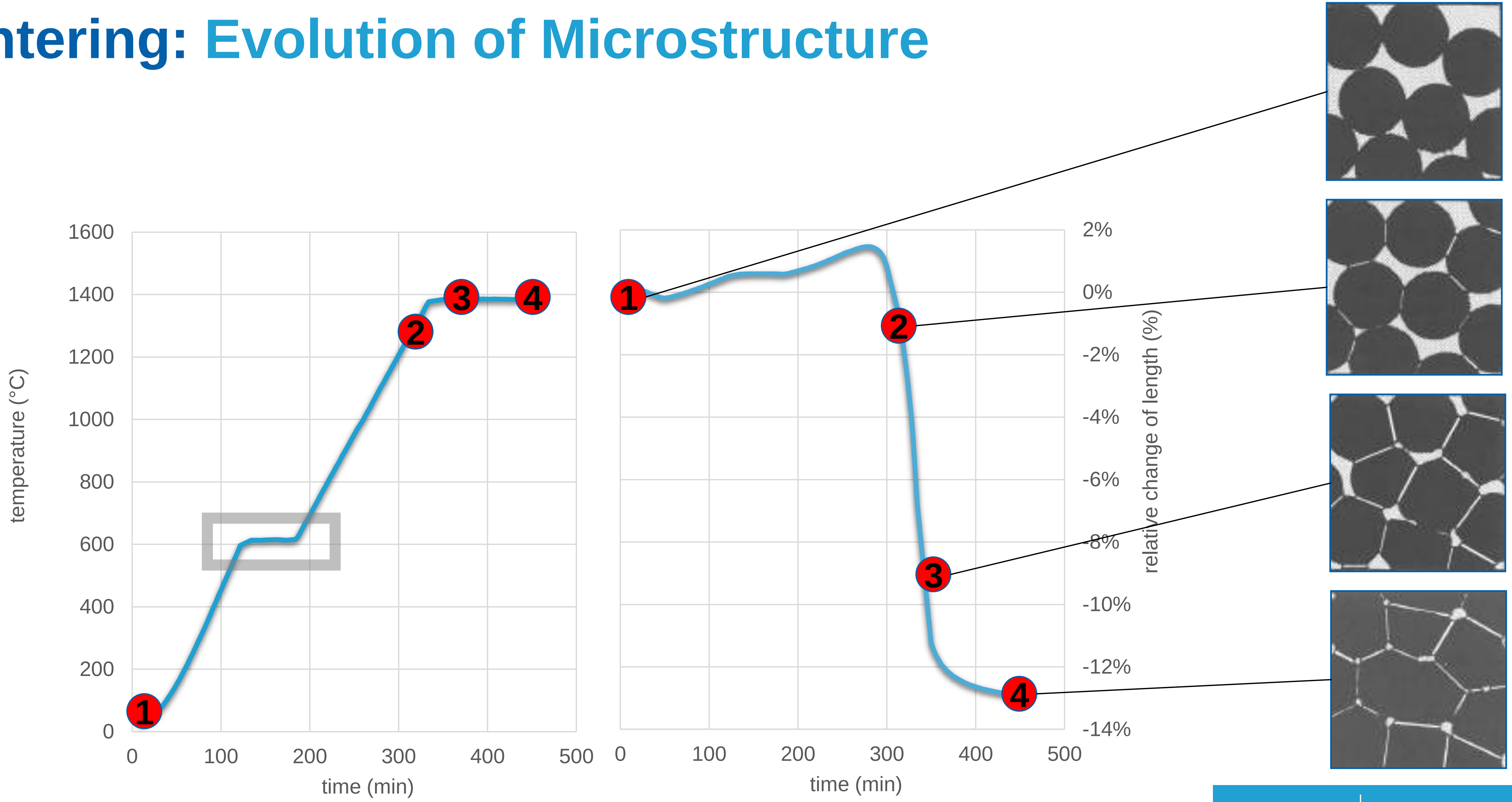
“Brown Part”

“Sintered Part”

16 - 20% shrinkage

- **Sintering**
  - The process of compacting and forming a solid mass of material by heat or pressure without melting (below temperature of liquid phase)
  - A volume / size decrease occurs as separate powder particles combine to produce a dense part
- **Final debinding**
  - Secondary binder or “backbone” decompose in presintering
  - Starting at 250°C and completely removed by 600°C (Valley of Death)

Sintering: Evolution of Microstructure



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Sintering: Equipment

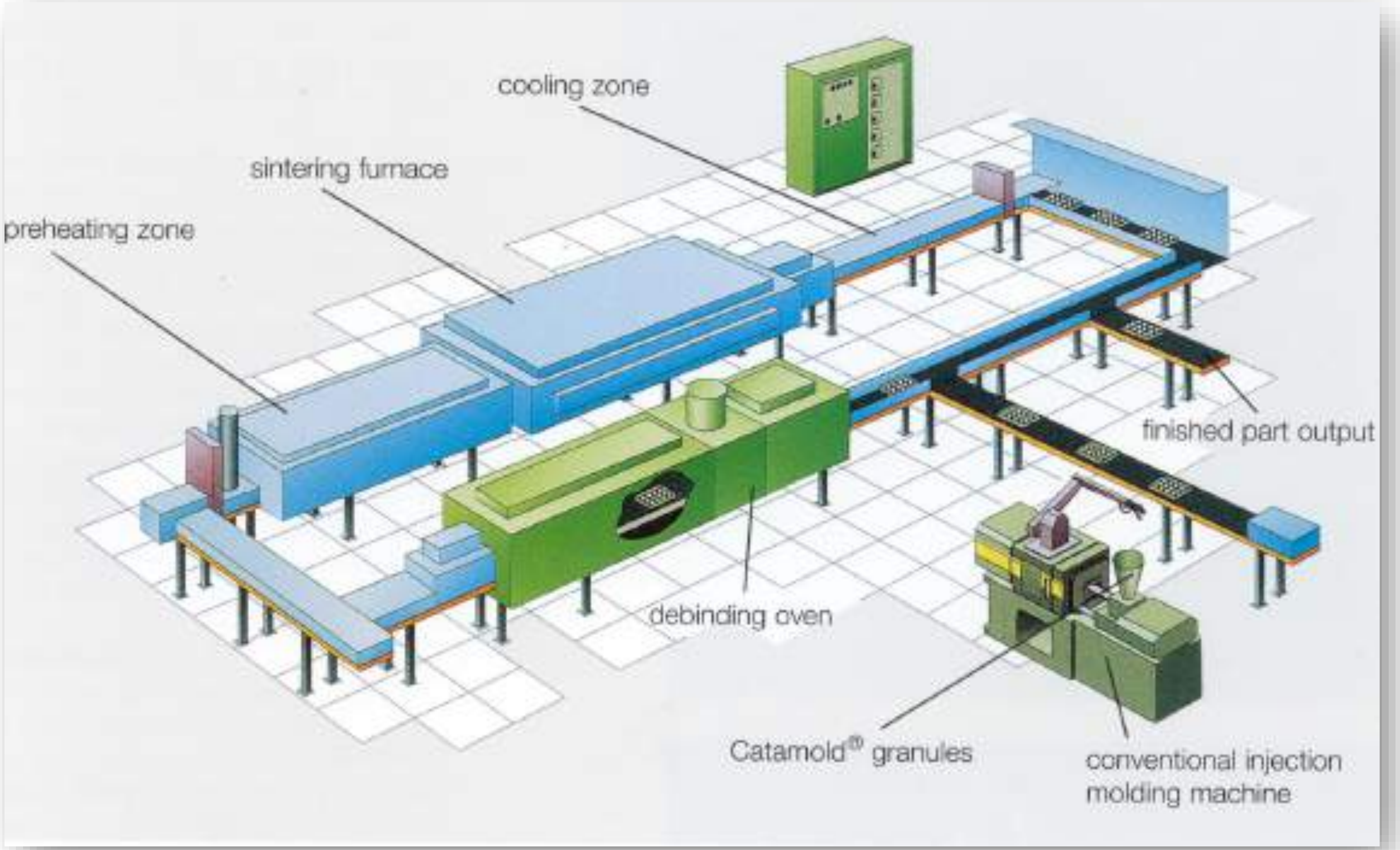
- **Sintering Ovens**
  - Modern sintering ovens are highly automated
    - Increased process stability
    - Ensure safe operation

- **Sintering atmosphere**
  - Dependent on material requirements (H2, N2, Ar, mixed gases, vacuum)
  - Ultrafuse 316L is sintered in H2 to ensure material composition (Carbon and Oxygen removal)
  - Carbon control required for 316L (0.03% C Max)

Source: www.nabertherm.com

Sintering: Equipment

- **Oven Types**
  - Both batch and continuous systems are available
  - Continuous systems are capable of both debinding and sintering in one system



Source: Catamold Feedstock for Metal Injection Molding: Processing - Properties - Applications

Introduction Summary

- **Feedstocks to Filament**
  - BASF has adapted MIM feedstock systems for use in common FFF 3D printers
  - MF³ makes possible full metal 3D printing with significantly lower capital investments
  - Enables the ability to make hollow / lightweight features in multiple materials; not currently possible with existing metal additive processes
- **Debinding & Sintering**
  - Catalytic debinding provides fast and efficient binder removal at industrial scale
  - Sintering solidifies debound “brown parts” to produce fully dense sintered parts
  - A reduction in part volume results from the sintering process

Ultrafuse 316L Design Guidelines

Design Guidelines: Overview

- **A Great Part Starts With Great Design**
  - The following process steps should be taken into account during part design / selection
- **Recommendations Not Limitations**
  - The guidelines are provided to increase the success rate of new users
- **Printing Is The Easy Part! D&S is Most Critical**
  - Many guidelines are motivated by the particular needs of the D&S process
- **Design Guidelines are a living document**
  - We continue to optimize our materials and process knowledge to continuously update and improve these guidelines
  - This current version is based mostly on:
    - 0.4mm Nozzles
    - 1.75mm filament
    - 100% infill

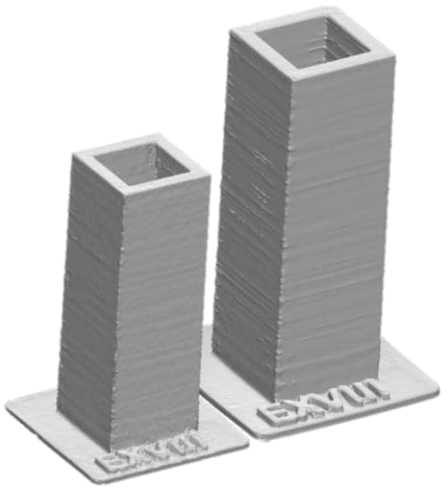
Part Size: Shrinkage & Scaling

- **Shrinkage & Scaling**
  - Parts shrink as a result of sintering
  - Shrinkage $\equiv \left(\frac{green - sintered}{green}\right) 100\%$
  - Oversizing factors are used to scale up green parts to provide accurate final parts

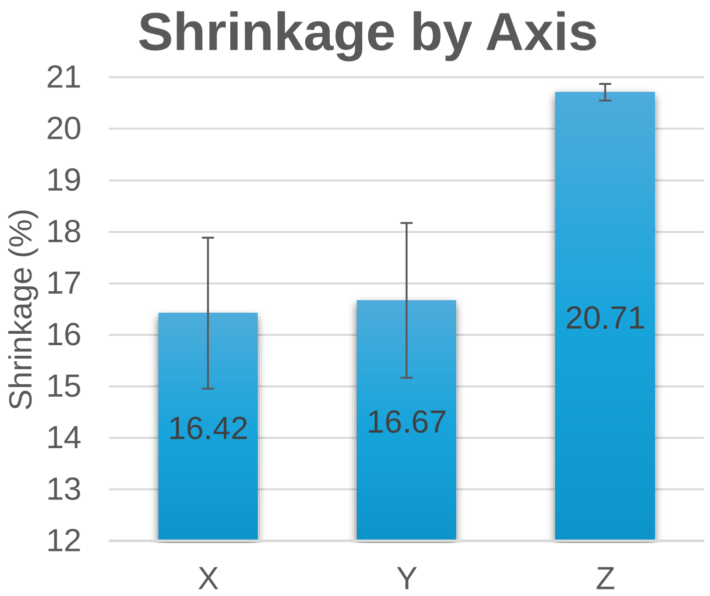
Printing Axis	Shrinkage (%)	Oversizing Factor
X	16.5±0.5	1.20
Y	16.5±0.5	1.20
Z	20.5±0.3	1.26

Typical Shrinkage & Scaling Values

- **Example: Experimental Towers**
  - 24 individual parts with various printing parameters to created largest variation of results
  - Shrinkage is also effected by geometry



(left) Sintered (right) green

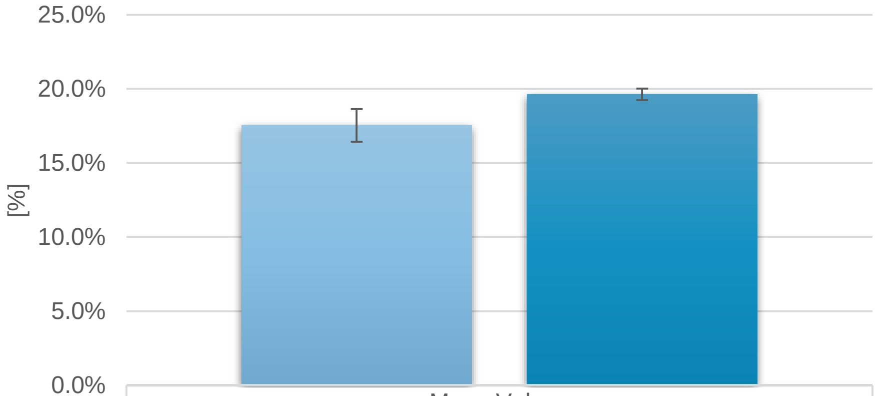


Part Size: Shrinkage & Scaling

Shrinkage & Scaling

- Parts shrink as a result of sintering
- Shrinkage $\equiv \left(\frac{green - sintered}{green}\right) 100\%$
- Oversizing factors are used to scale up green parts to provide accurate final parts

Chess Knight; Shrinkage

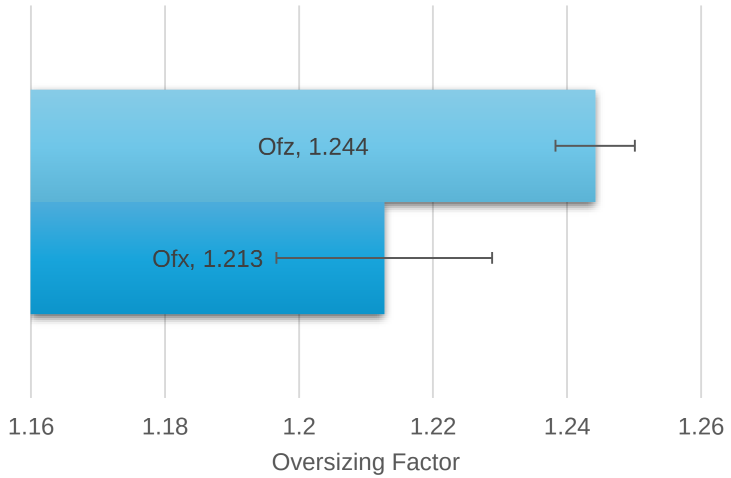


	Mean Values
Sx%	17.53%
Sz%	19.63%

Oversizing Factor:

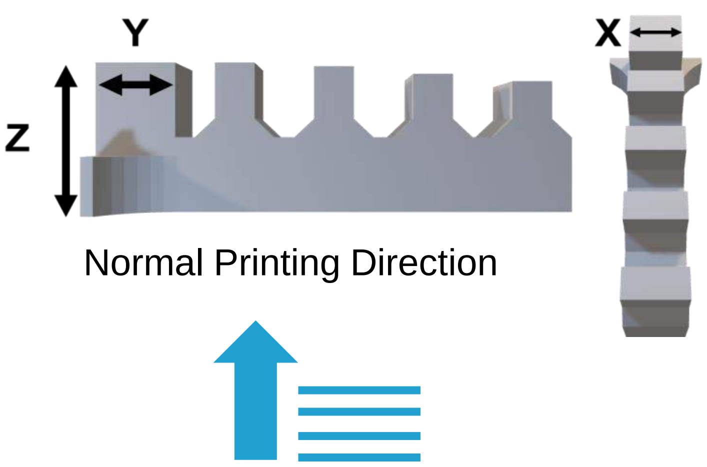
- $Of_x \equiv \left(\frac{X_{green}}{X_{sintered}}\right)$
- Corrected oversizing factor

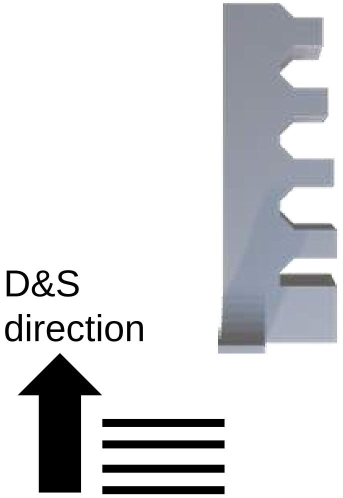
Actual Oversizing Factor



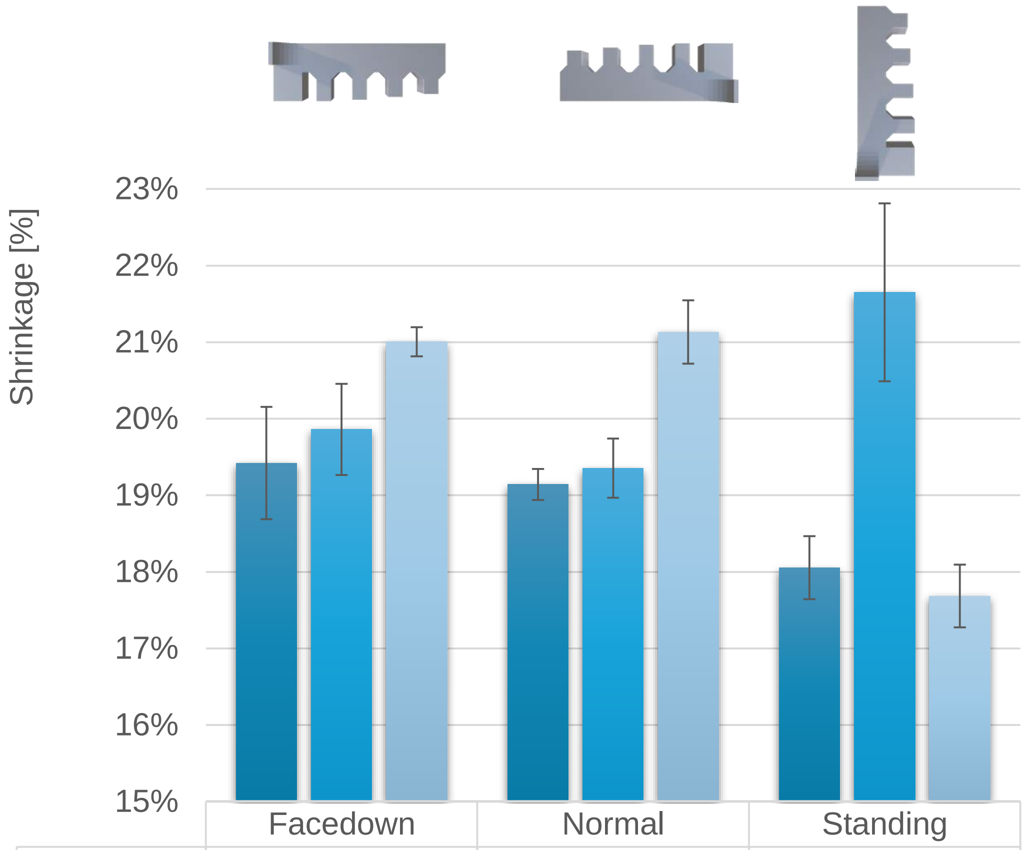
Part Size: Shrinkage & Scaling

- **Shrinkage & Printing Orientation**
  - The Z -Direction will have the greatest shrinkage
  - This effect is independent of D&S orientation
  - The examples seen on right were printed in different orientation but sintered standing





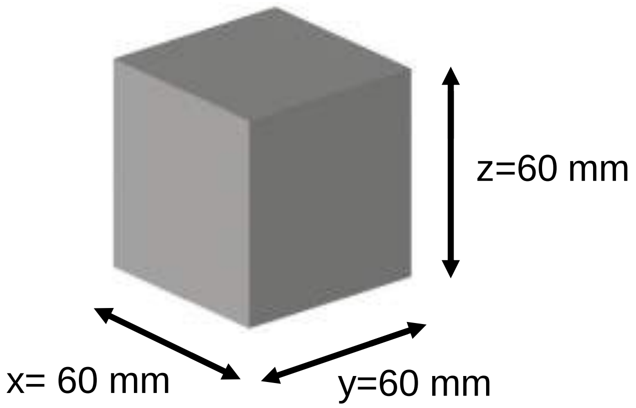
Average Percent Shrinkage by Printing Orientation (All sintered in Standing orientation)



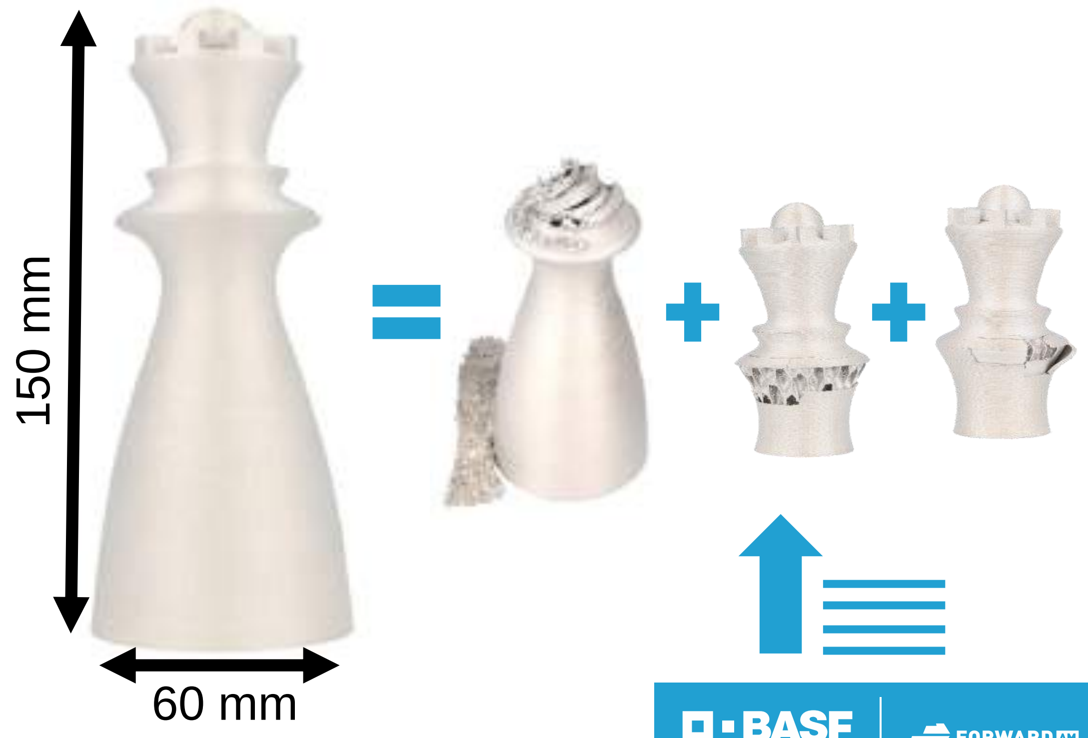
	Facedown	Normal	Standing
X %Shrink	19.42%	19.14%	18.05%
Y %Shrink	19.86%	19.35%	21.65%
Z %Shrink	21.00%	21.13%	17.68%

Part Size: Max Suggested Build Volume

- **Max Suggested Green Part Size**
  - The 60mm cube has proven to be most successful for beginner parts
  - Parts larger the X145mm &/or Y145mm require customer handling / extended lead times
    - Processing maybe subject to D&S provider approval

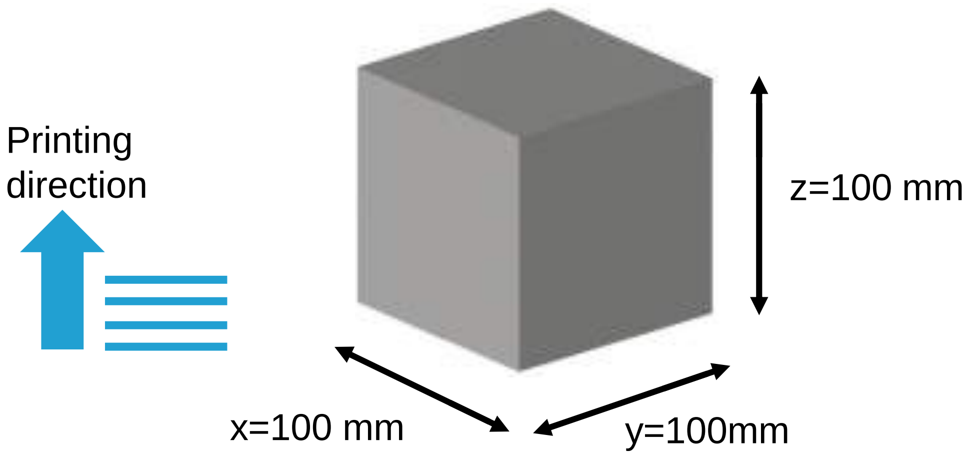


- **Example: Big King**
  - After multiple iterations this part was possible (month of development required)

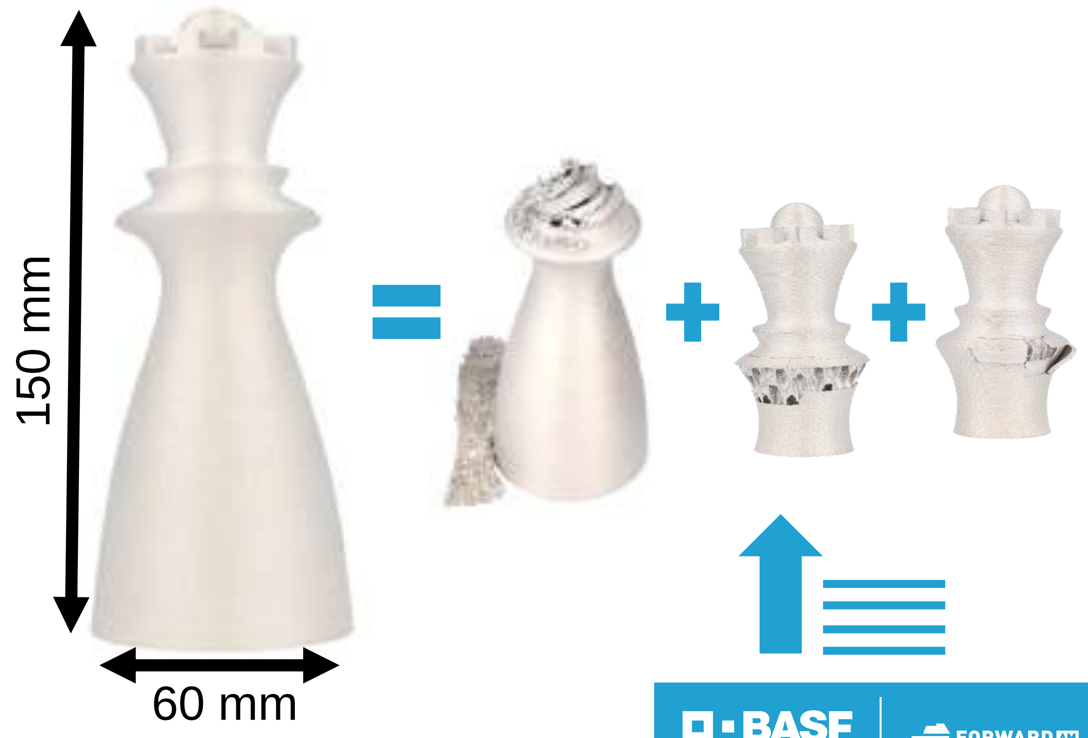


Part Size: Max Suggested Build Volume

- **Max Suggested Green Part Size**
  - Bigger the part the less its chance of survival
  - Parts larger than standard sintering plates will require customer handling / extended lead times

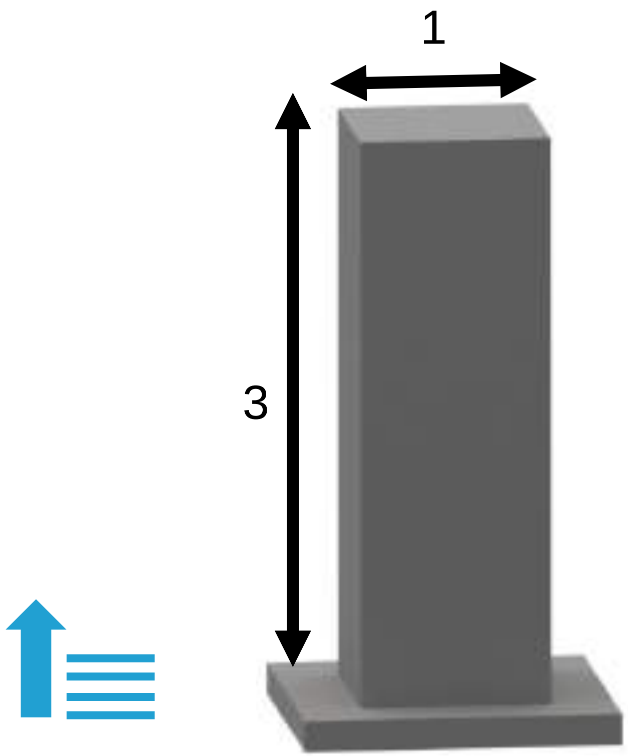


- **Example: Big King**
  - Parts outside the suggested size often require multiple job cycles

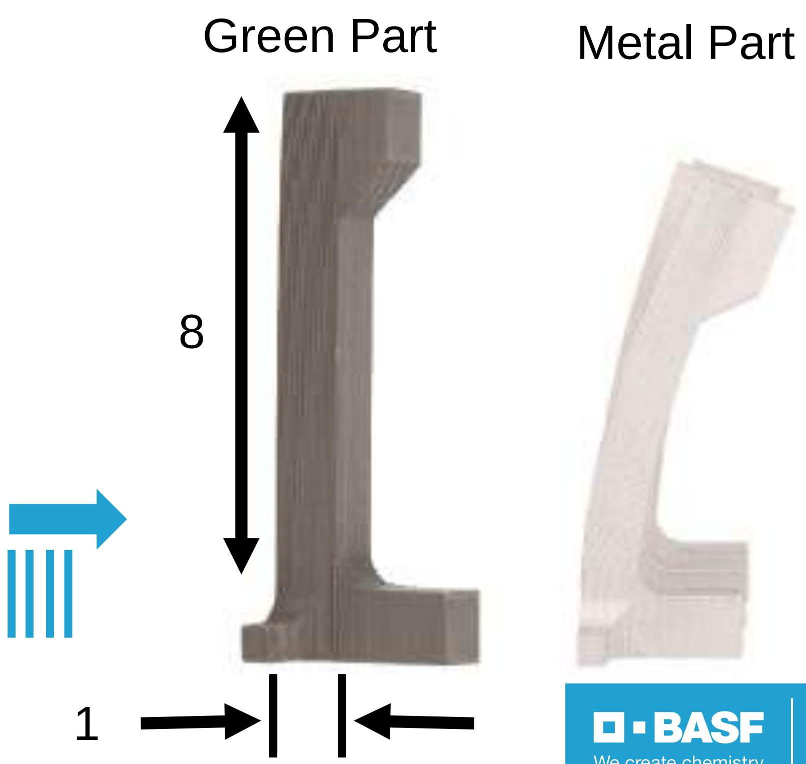


Height to Width Ratio

- **Height to Width Ratio**
  - Height to width ratios no larger than 3:1 have proven to be effective in preventing collapse or distortion during D&S

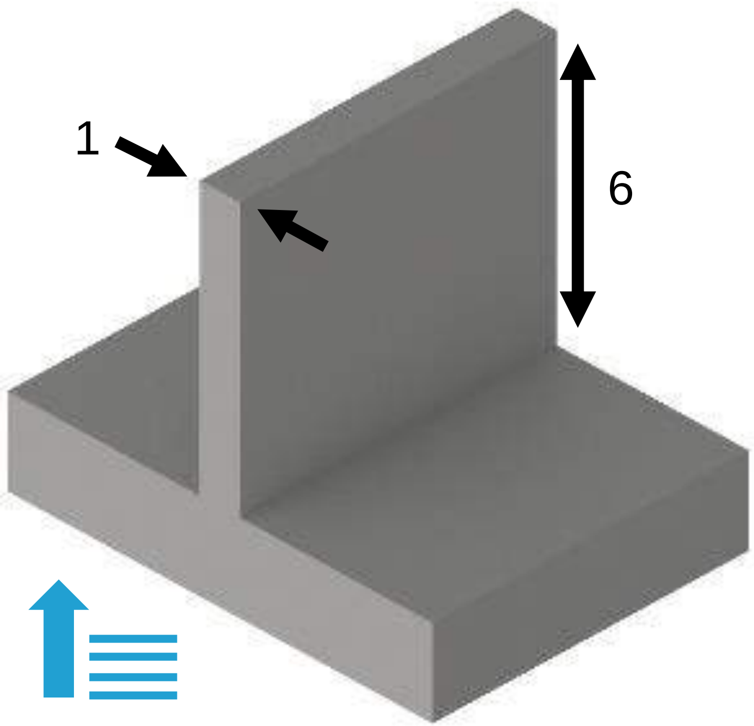


- **Example: Viscosity Tower**
  - With a height to width ratio of 8:1, this part show significant distortion during D&S

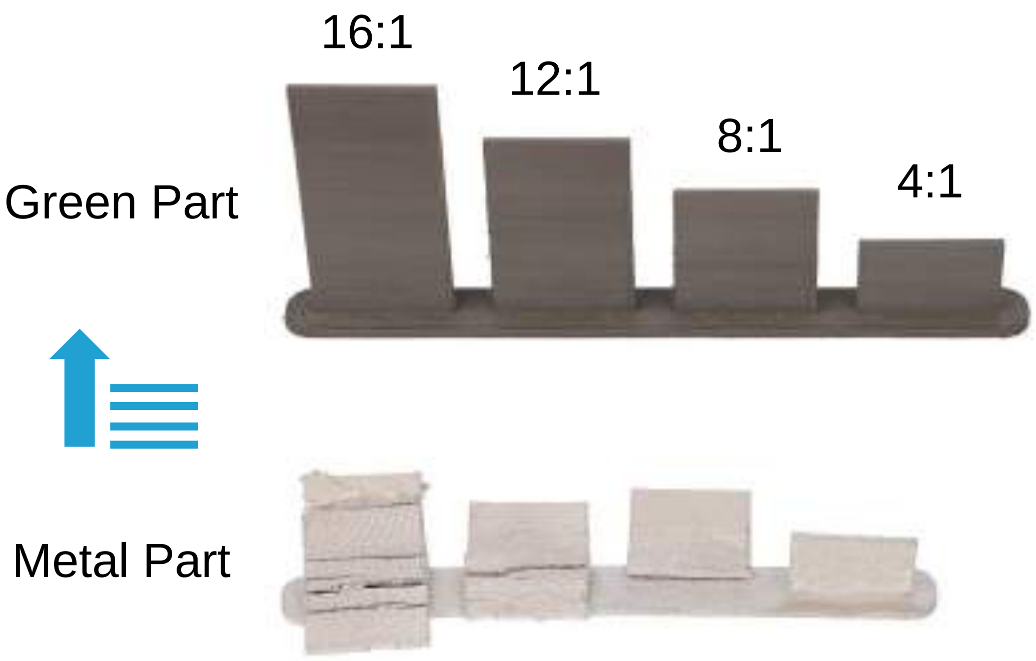


Unsupported Walls

- **Unsupported Thin Walls**
  - To minimize the chance of structural collapse, height to width ratios no greater than 6 to 1 have been proven to be effective

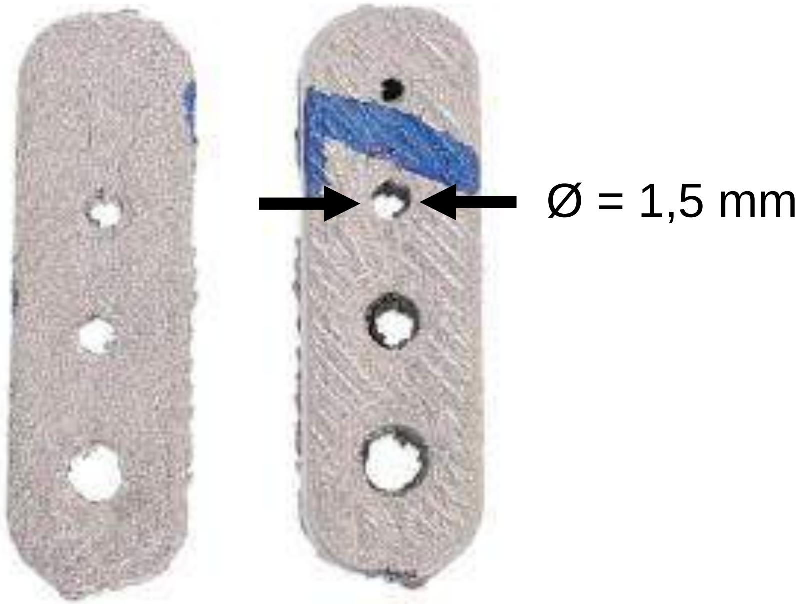


- **Example: Thin Wall Test**
  - Although easily printable, thin unsupported walls can fail when greater than 6:1



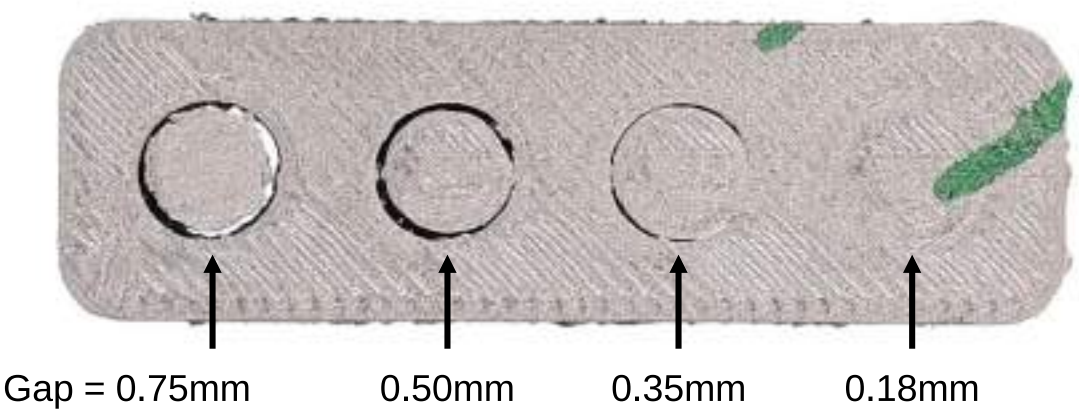
Vertical Holes

- **Vertical Through Holes**
  - Hole diameter can be reduced by over extrusion or poor first layer application
  - Diameters larger than 1.5mm have been found to be most achievable



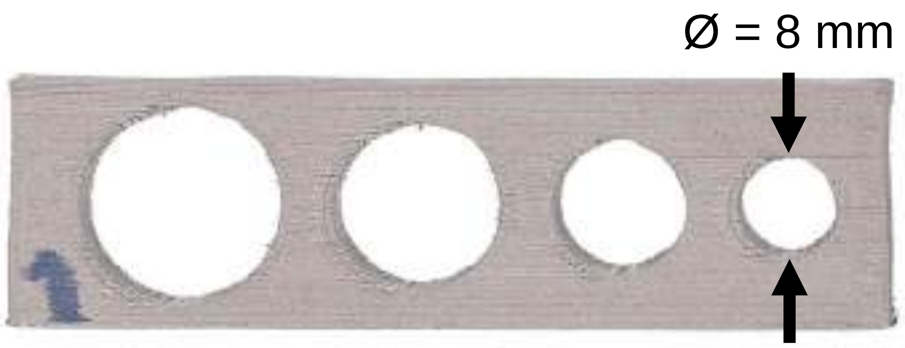
bottom top

- **Minimum Gap Between Parts**
  - Separate parts will be welded together during sintering if not given an appropriate amount of separation
  - 0.75mm are a good starting gap

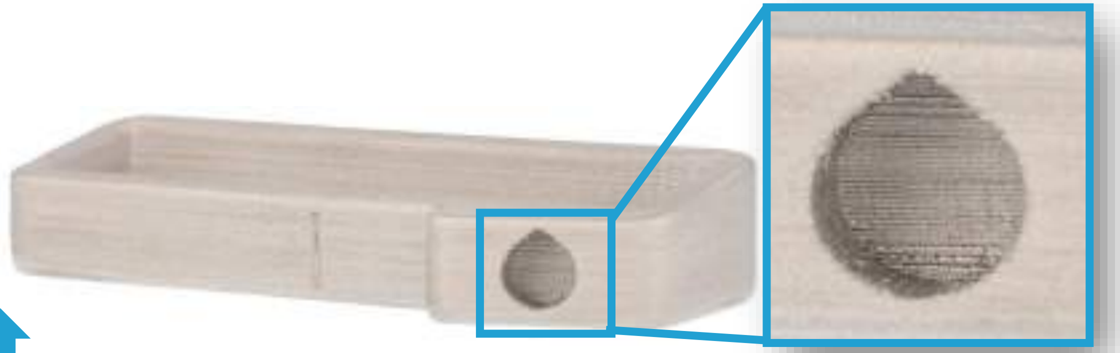


Horizontal Holes

- **Unsupported Horizontal Holes**
  - Typically, holes under 8mm dia. can be created without support structure
  - Larger diameters should be supported or changed by raindrop shape to prevent distortion or collapse in D&S

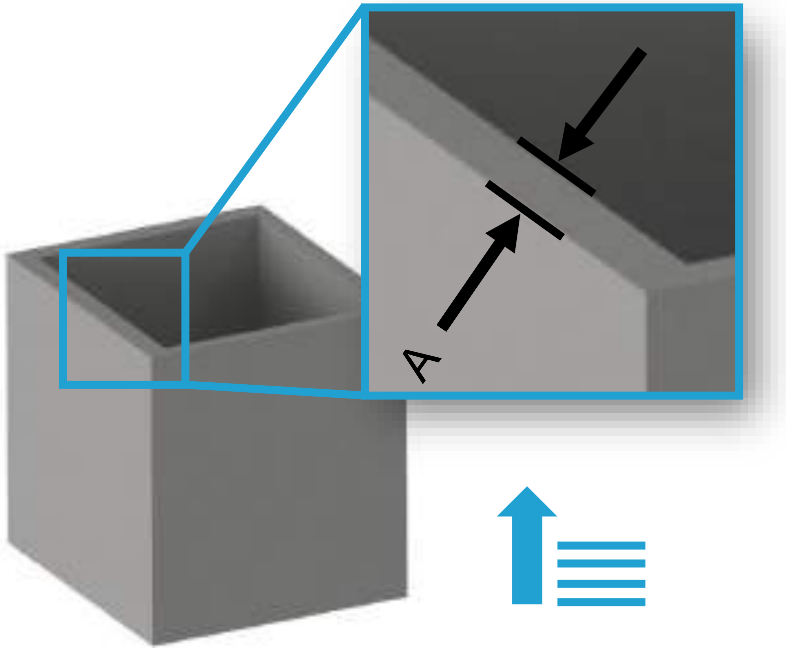


- **Part Example: Golf Putter**
  - 13mm blind hole required
  - The 45° overhangs are easily created and provide increased stability without the need for supports

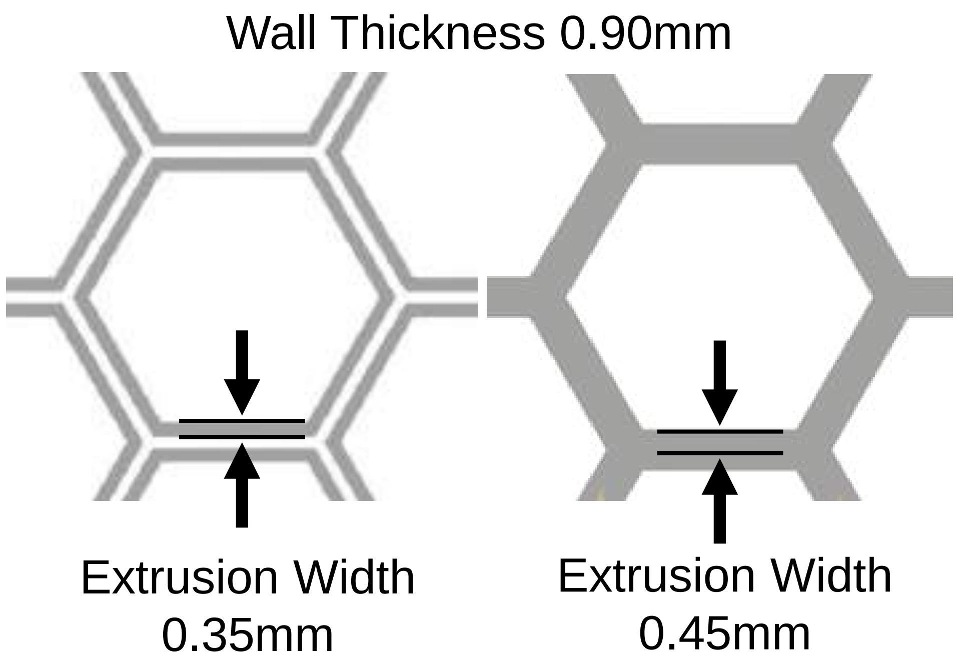


Extrusion Width

- **Thin Features**
  - Features should be a whole number multiple of the printer's extrusion width
  - $A = N * (Extrusion\ Width),$
    - $Where\ N = (2,3,4\ldots)$



- **Example: Poor Wall Connection**
  - Typical result of improper connection between outlines



Extrusion Width:

- **Thin Features**
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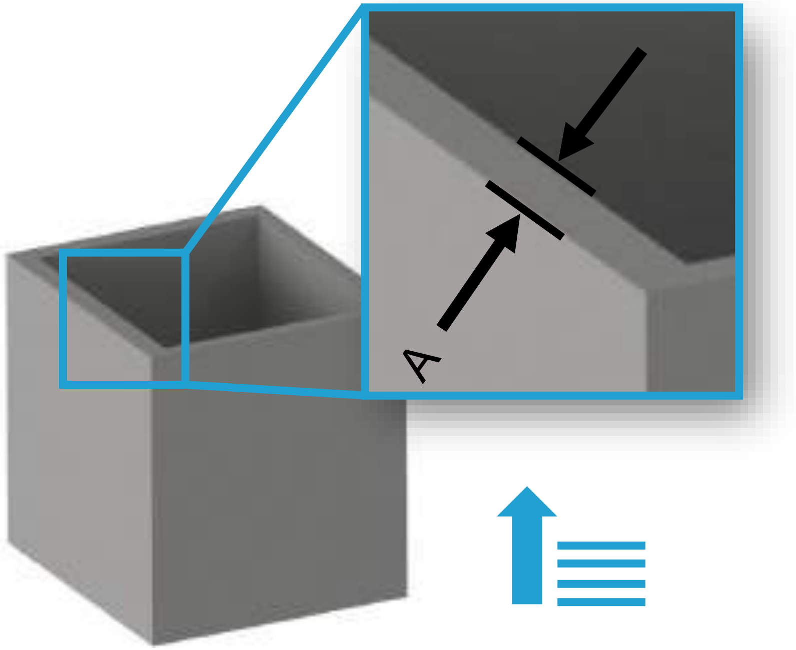
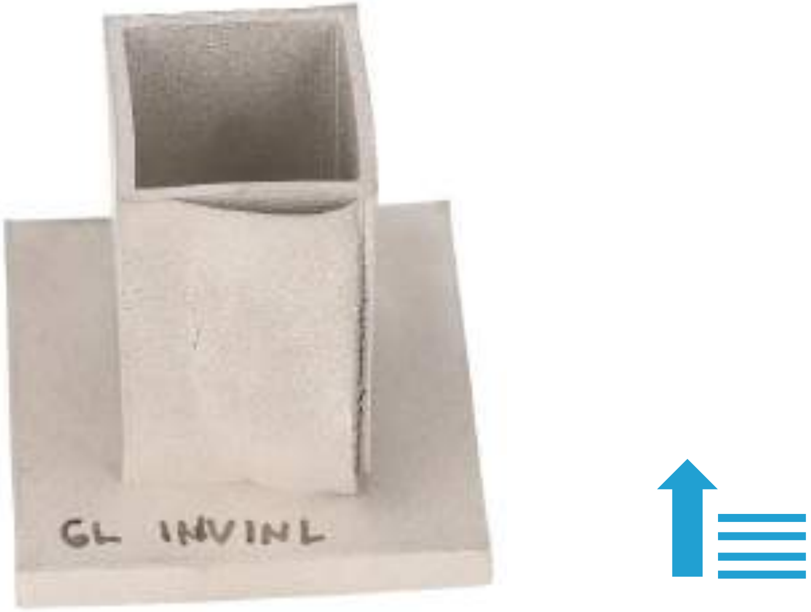


- **Example: Wall Separation**
  - Poor connection between vertical segments can result in separation



Extrusion Width

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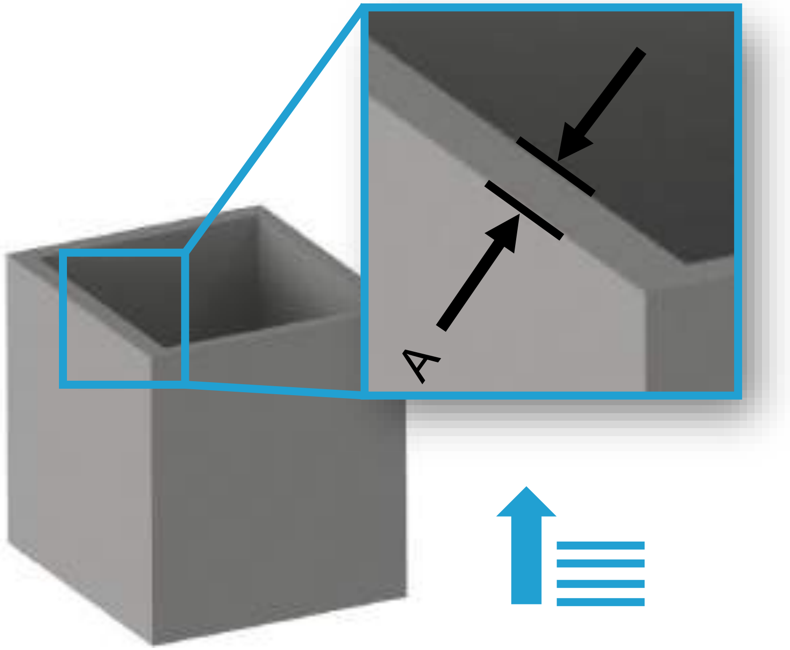
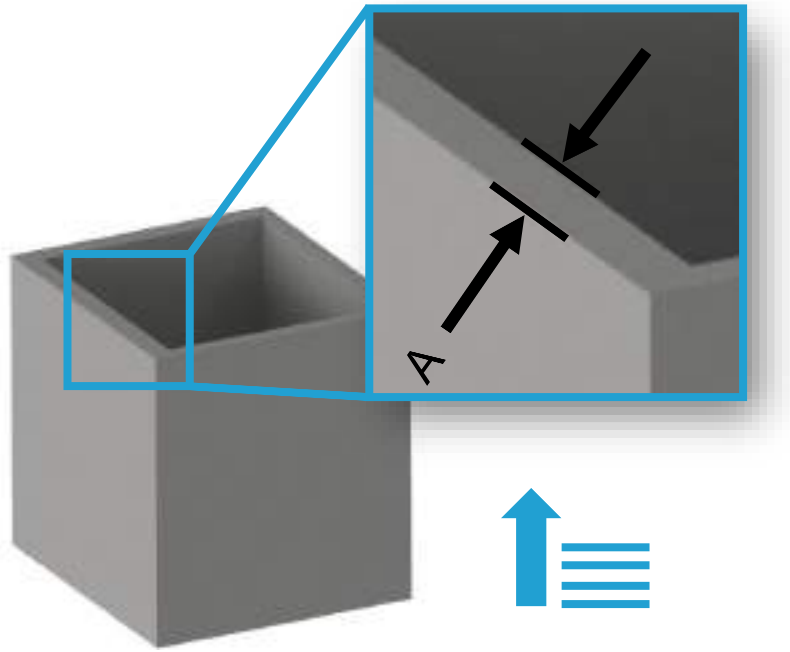


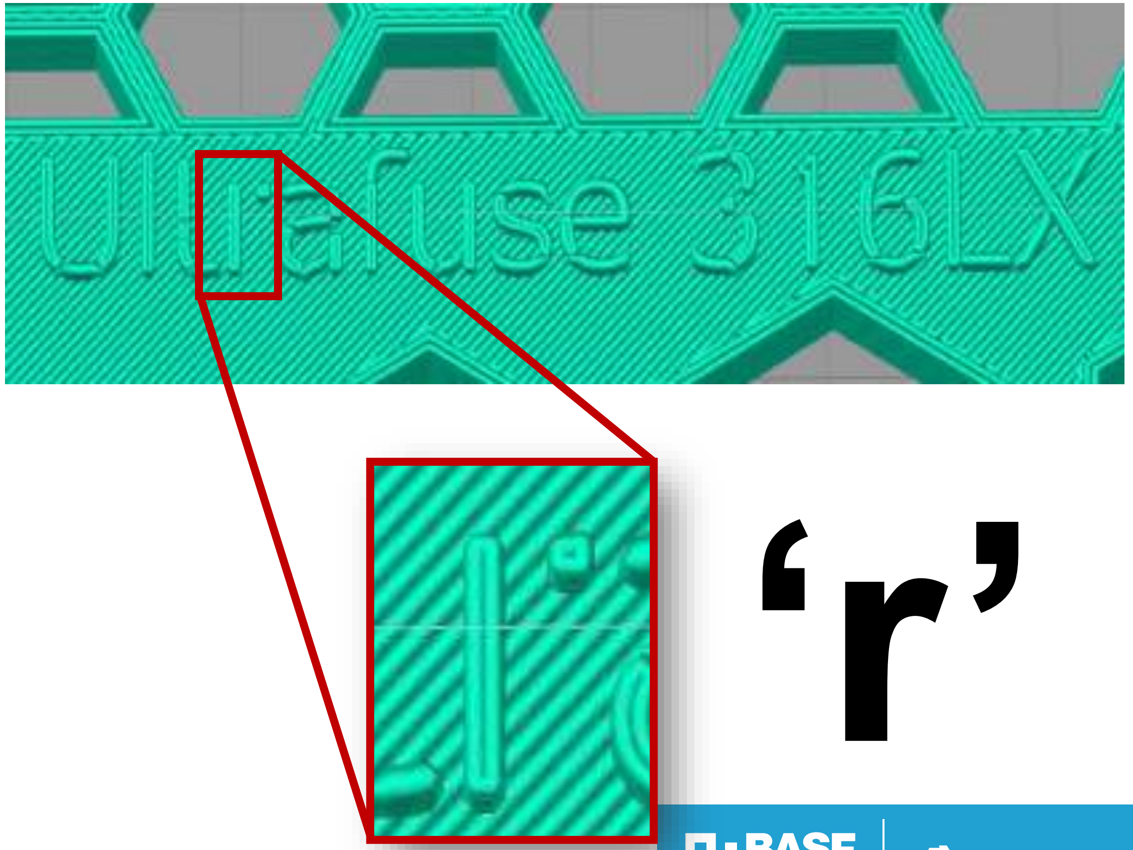
- **Example: Wall Distortion**
  - Single extrusion with tower (0.45mm)
  - Distortion and partial failure in D&S

Extrusion Width

- **Thin Features**
  - Features should be a whole number multiple of the printer's extrusion width
  - $A = N * (Extrusion\ Width),$
    - $Where\ N = (2,3,4\ ...\ )$

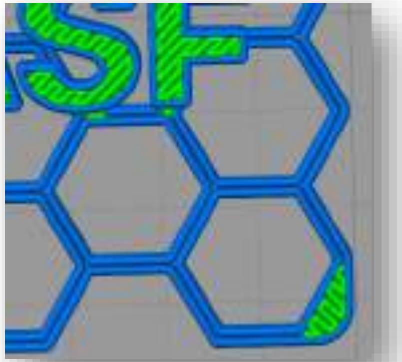


- **Example: Feature Loss**
  - Thinner portion of the 'r' not printable

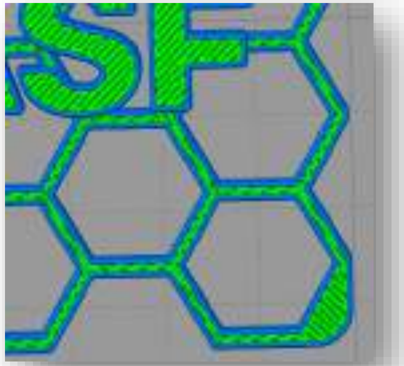


Extrusion Width

- **Scaling Must Be Considered**
  - Scaling up parts for shrinkage can effect extrusion width’s effectiveness

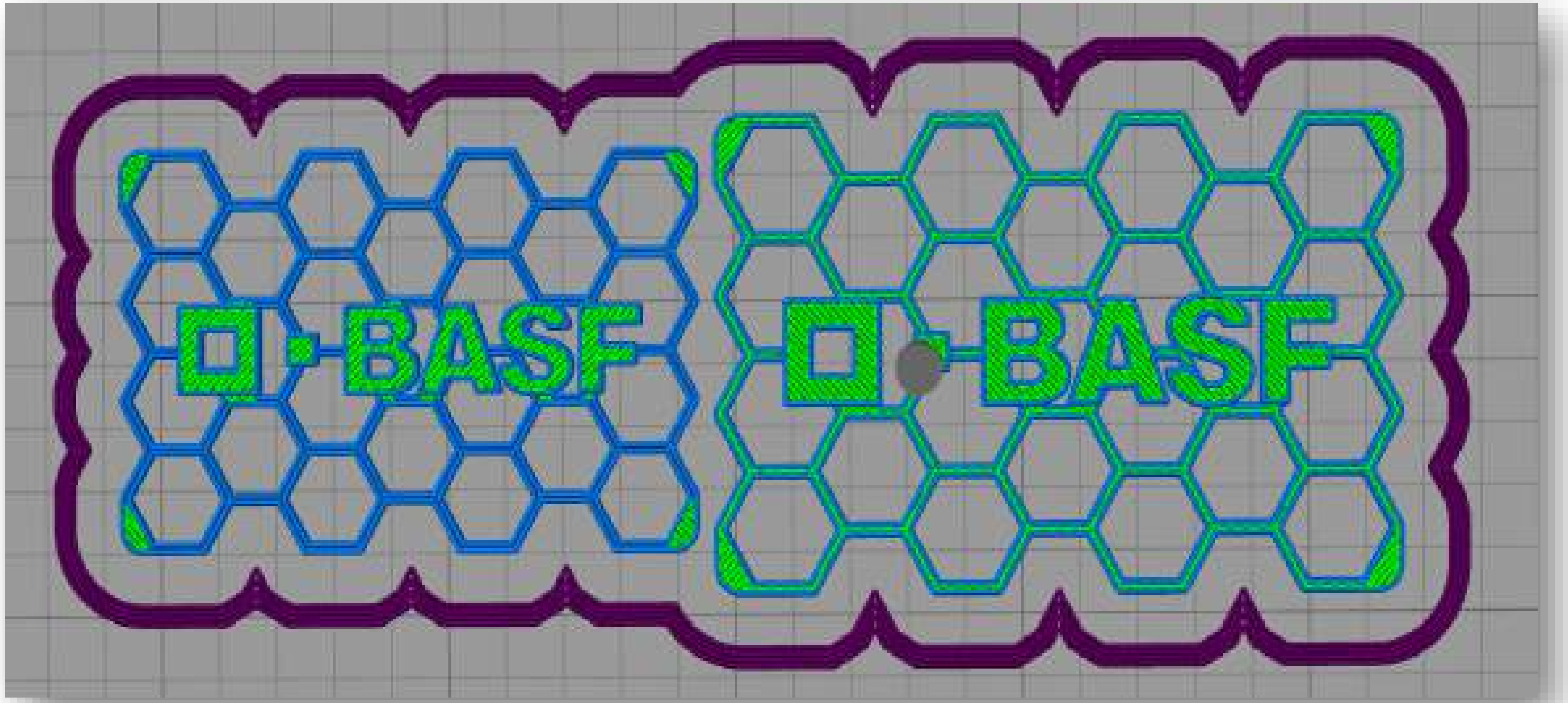


EW 0.48 mm



EW 0.35 mm

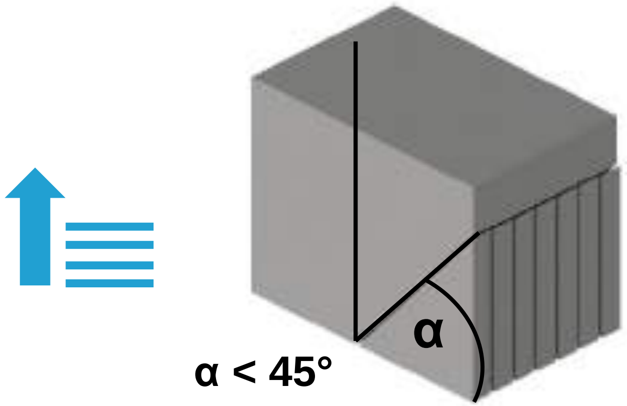
Original Size   Scaled



EW 0.48 mm

Supports: Not Just For Printing

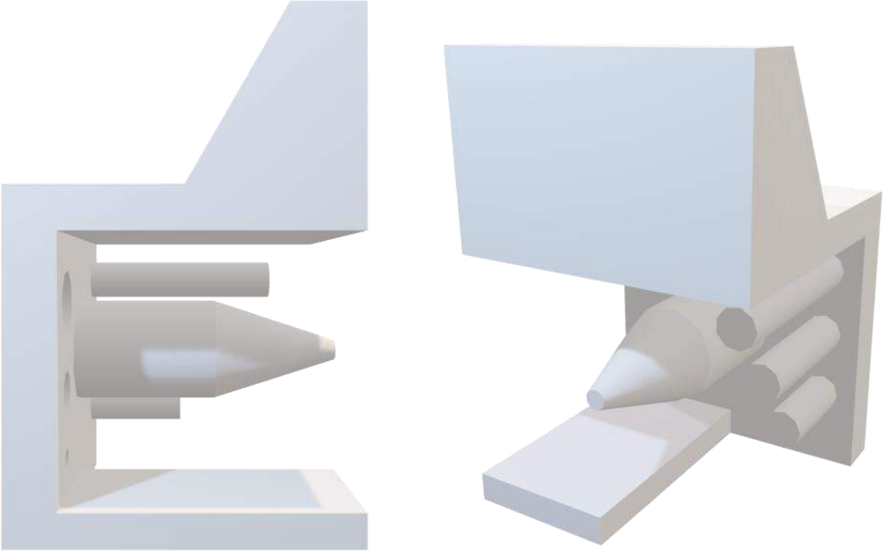
- **Overhangs (More Support for D&S)**
  - A greater need for supports is required in D&S than in printing
  - Angles less than 45° from the build platform require supports
  - Full density supports help to minimize the chance of collapse in D&S

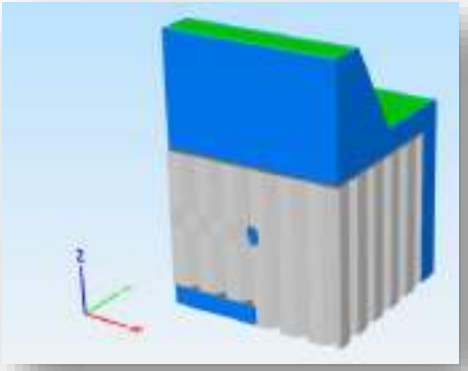


- **Part Example: Robot Gripper**
  - Early versions of this robot gripper made use of full and partial supports

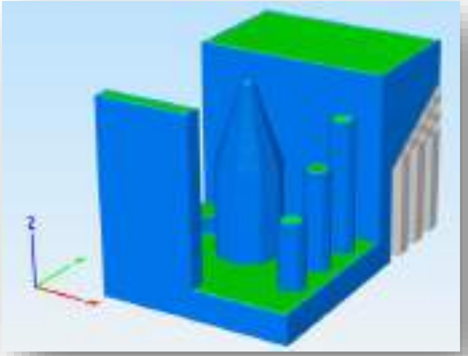
Supports: Balance Time & Safety

- **Overhangs (More Support for D&S)**
  - A greater need for supports is required in D&S than in printing
  - Angles less than 45° from the build platform require supports
  - Full density supports help to minimize the chance of collapse in D&S





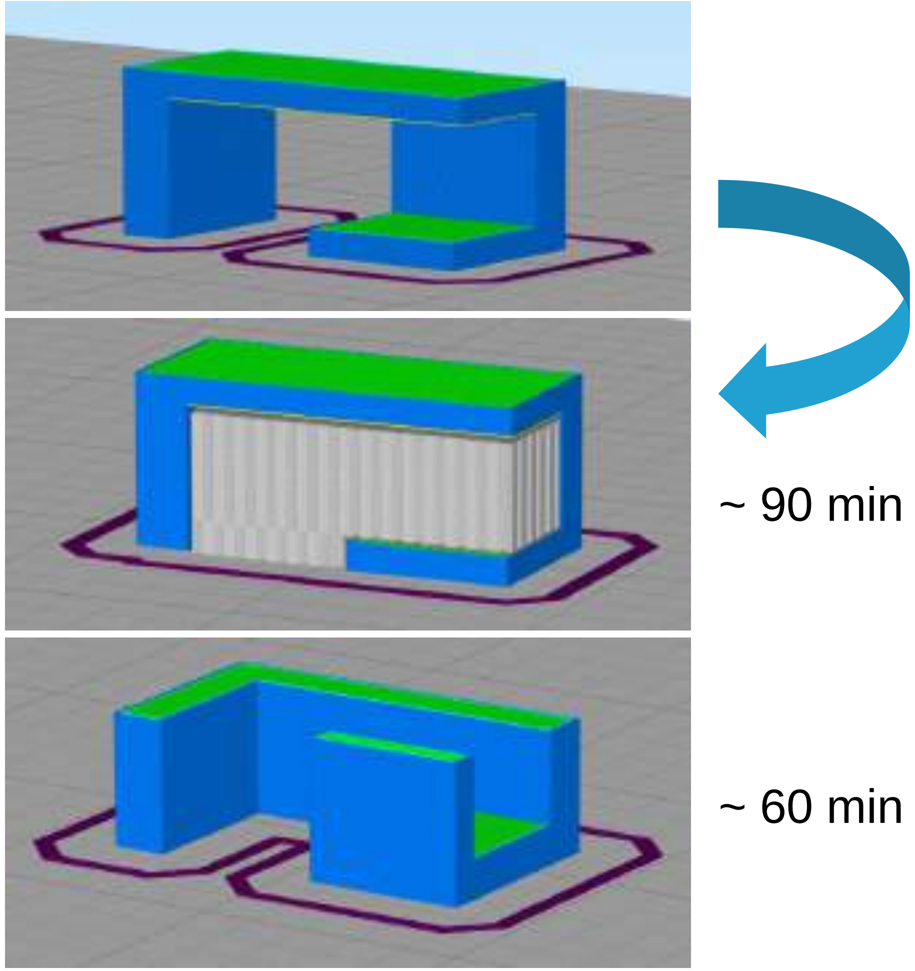
- **Option 1:**
  - Time = 163 min
  - Max support



- **Option 1:**
  - Time = 139 min
  - Minimum support

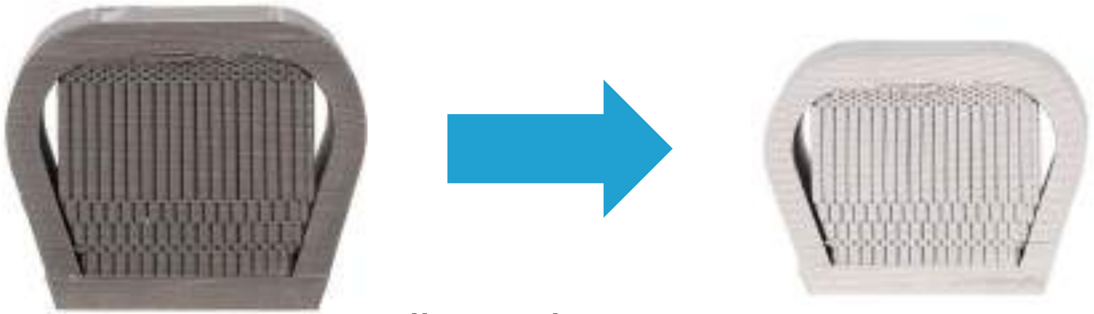
Supports: Balance Time & Safety

- **Overhangs (More Support for D&S)**
  - A greater need for supports is required in D&S than in printing
  - Angles less than 45° from the build platform require supports
  - Full density supports help to minimize the chance of collapse in D&S

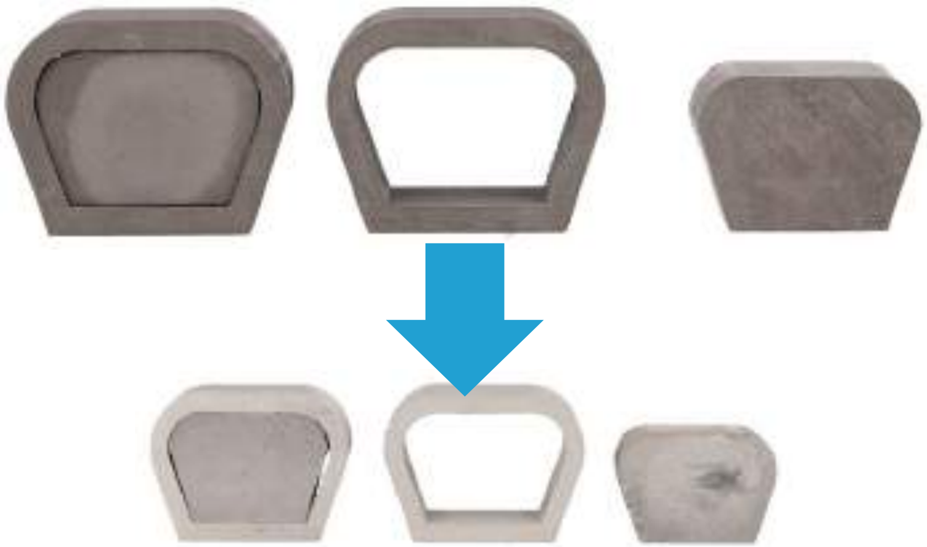


Supports: Balance Time & Safety

- **Support Types**
  - Full metal supports require post-sintering removal similar to tradition powder-based metal 3D printing methods
    - CNC or other postprocesses required
  - Separation spray can be manually applied before D&S
    - Common practice in MIM
    - A sintering



Full Metal Supports



Separation Spray Supports

Supports: Balance Time & Safety

- **Support Types**
  - Full metal supports require post-sintering removal similar to DMLS / SLM
    - CNC or other postprocesses required
  - Separation spray can be manually applied before D&S
    - Common practice in MIM
  - Dual extrusion ceramic supports
    - Full density supports help to minimize the chance of collapse in D&S

Separation Spray

Ceramic Supports

Flat Bottom Surface

- **Bottom Surface Must Be Flat**
  - Warped bottom surfaces can cause parts to tilt or even collapse in D&S
  - Sanding is the easiest method to ensure a flat surface
- **Part Example: Chess Bishop**
  - Warpage during printing was removed by sanding for the left but not the right

Design Guidelines: Documentation

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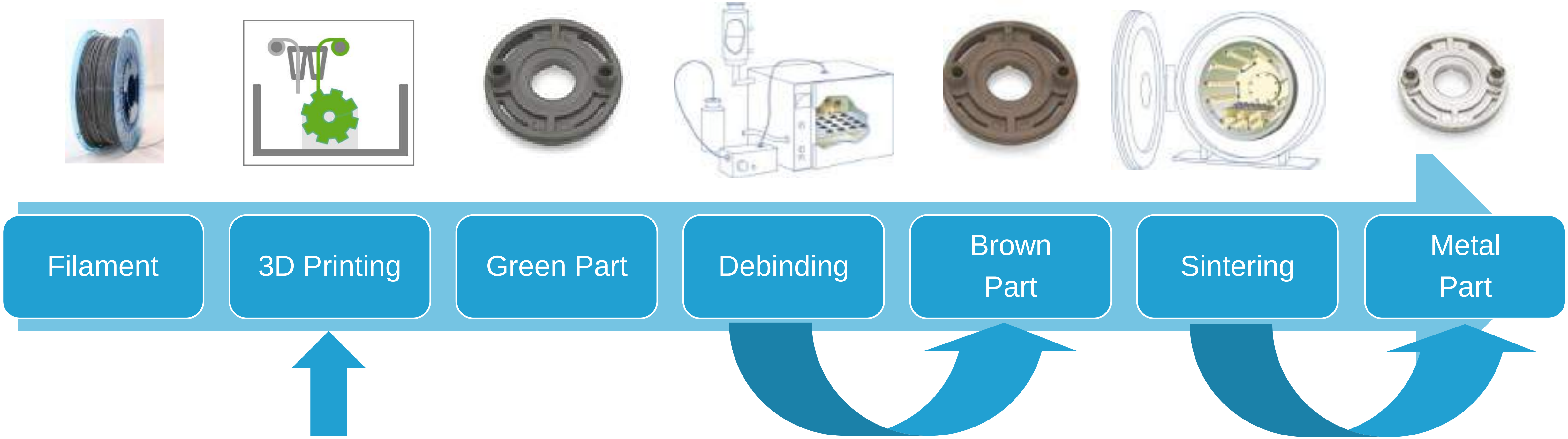
Summary: Design Guidelines

- **Although general scaling factors are provided, shrinkage is effected by geometry**
- **Parts must be within 100mm bounding box to reduce part loss and rework**
- **Appropriate height to width ratios have proven to be effective in preventing failures**
- **Extrusion width is a critical printing parameter that can effect:**
  - Layer separation / part failure in D&S
  - Geometric accuracy
  - Print time
- **Supports are not just for printing, they reduce distortion and failure during D&S**
- **Bottom surface must be flat; warped bottom surfaces can cause tilt or collapse**

Simulations & Virtual Engineering

Process Workflow: Feedstock to Part



Risk of collapse

Anisotropic shrinkage & Risk of distortion

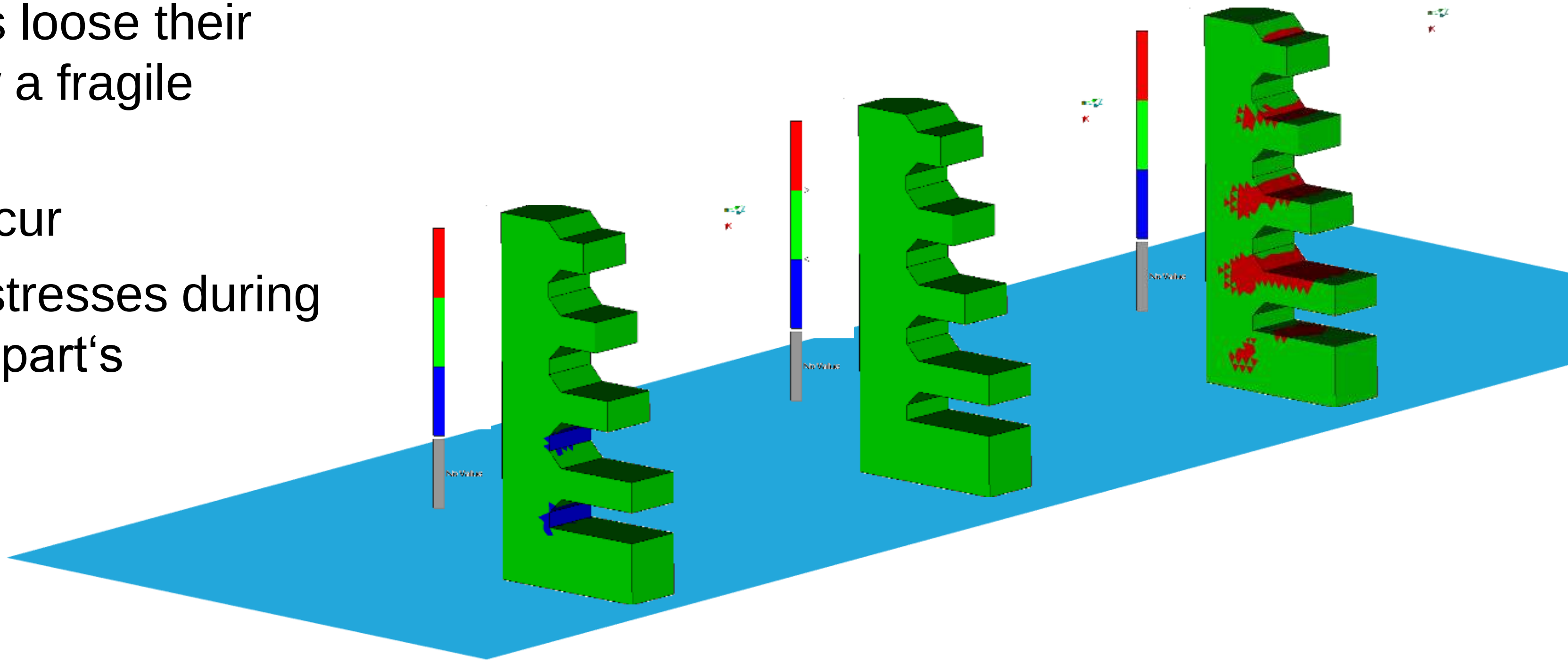
- **Design Guide**
  - Part size / supports
  - Scaling
  - Extrusion width
  - Print orientation

Virtual Engineering Workflow

- **Process Needs**
  - Brown part stability to detect critical stressed areas during debinding
  - Orientation Simulation for complex parts
  - Sinter simulation to ensure dimensional accuracy

Brown Part Stability Analysis

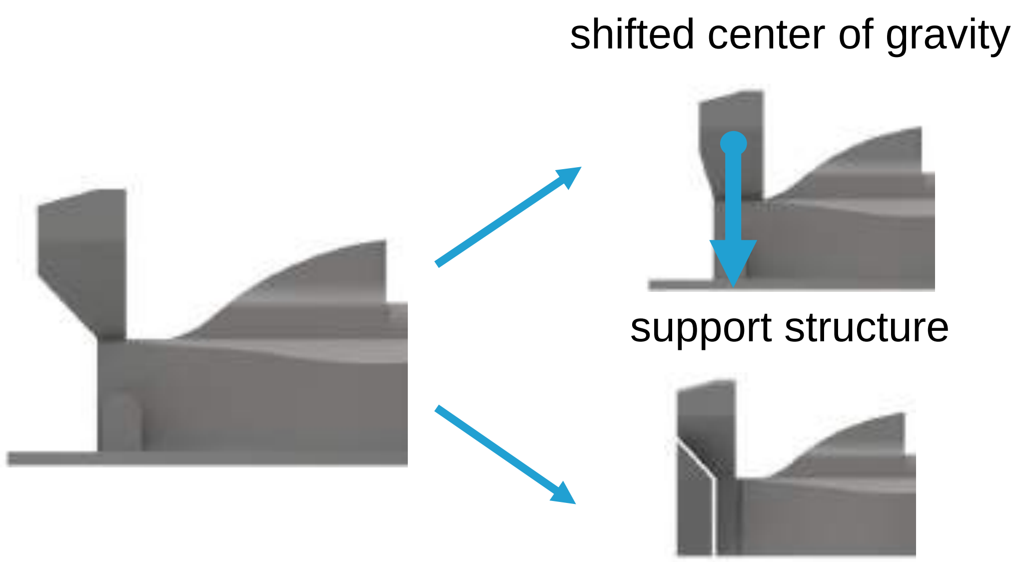
- **Debinding Stability Check**
  - During debinding green parts loose their stabilizing polymer and show a fragile behavior.
  - Breakage or collapse can occur
  - Brown part analysis checks stresses during debinding and evaluates the part‘s survivability.
    - Pass - Fail



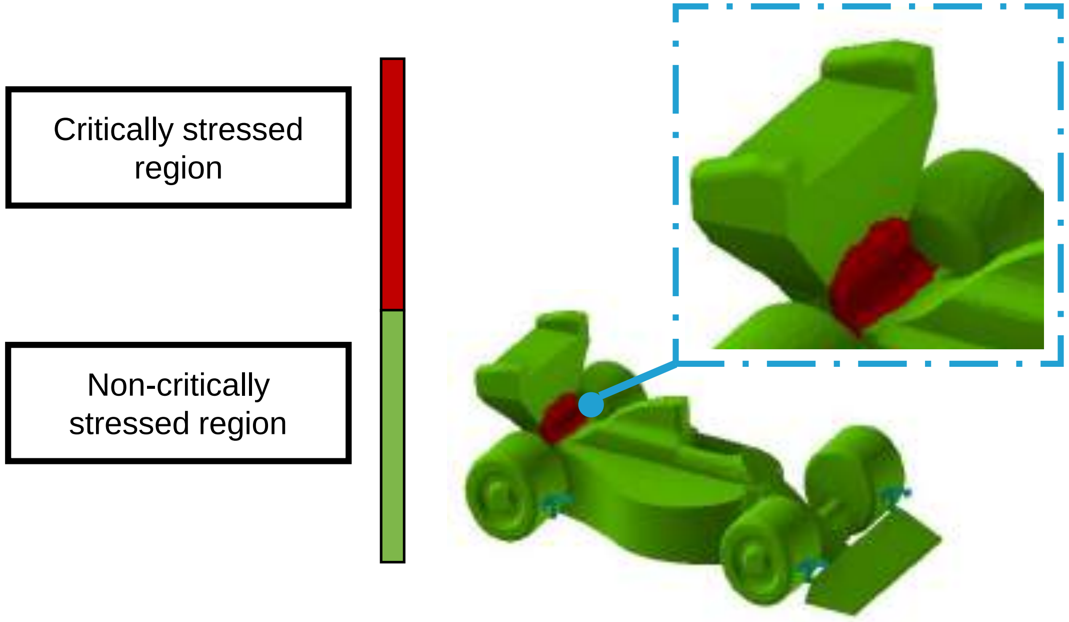
Analysis of internal stresses during debinding

Brown Part Stability Analysis
Design Guide Informed by Simulation

- **Overhangs (More Support for D&S)**
  - A greater need for supports is required in D&S than in printing



- **Brown Part Stability**
  - Brown Part Stability helps to detect highly stressed areas to make design changes

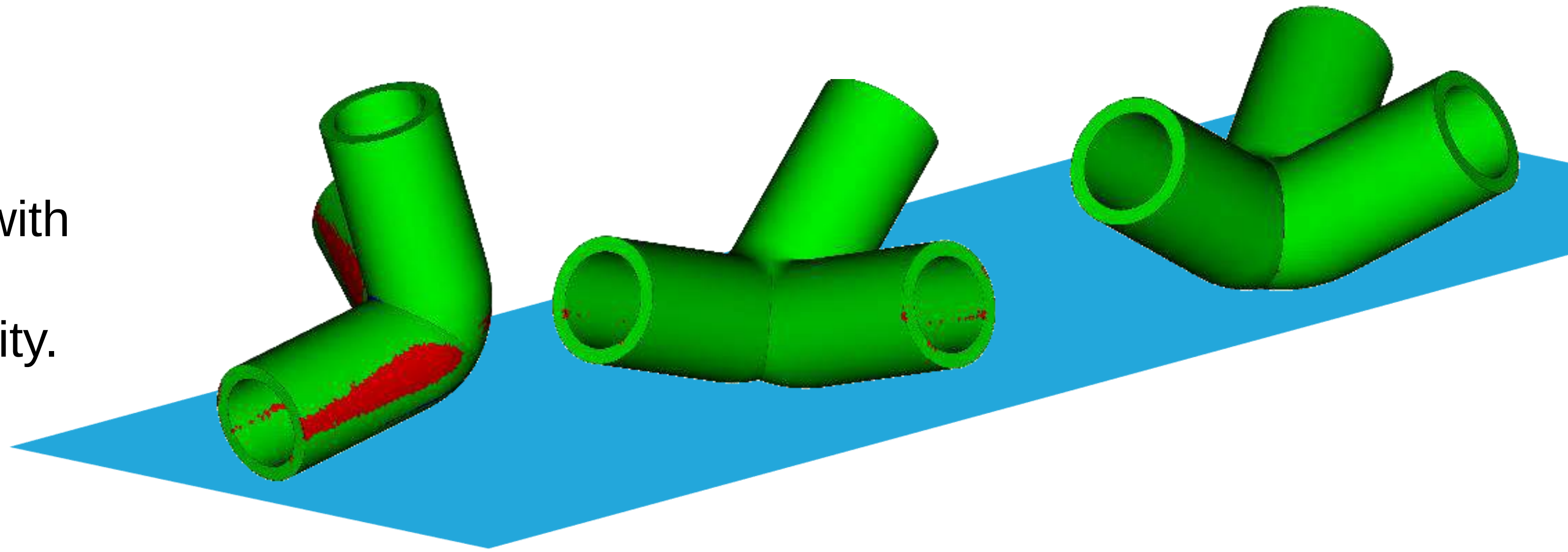


Brown Part Stability Analysis: Orientation Optimization

Finding the optimal print orientation

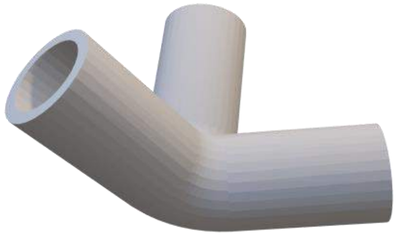
If a part design cannot be changed, we can apply our debinding orientation optimization to find an optimal part orientation during debinding.

This will provide a part orientation with minimal internal stresses and consequently the highest survivability.



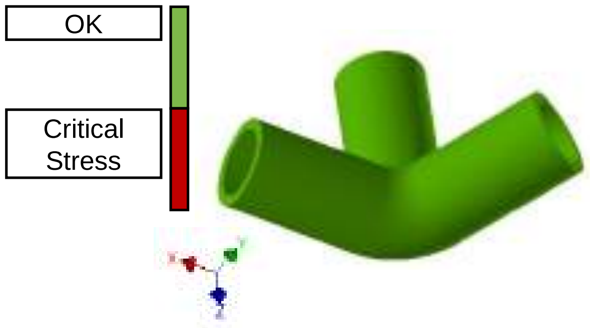
Different orientations and their resultant stress states

Part Orientation: Best Guess

CAD Design	3D Printing	D&S
		
• In case of complex parts the optimum orientation of minimum internal stress within a part has to be found	• Usually it is sufficient to align parts according to experience (looking for flat faces a.s.o)	• However, this can lead to iterative repetitions with complex parts

Part Orientation: Simulations

Simulation



- Several hundred alignments are tested to find the optimal orientation
- Lowest stress in the component.

3D Printing

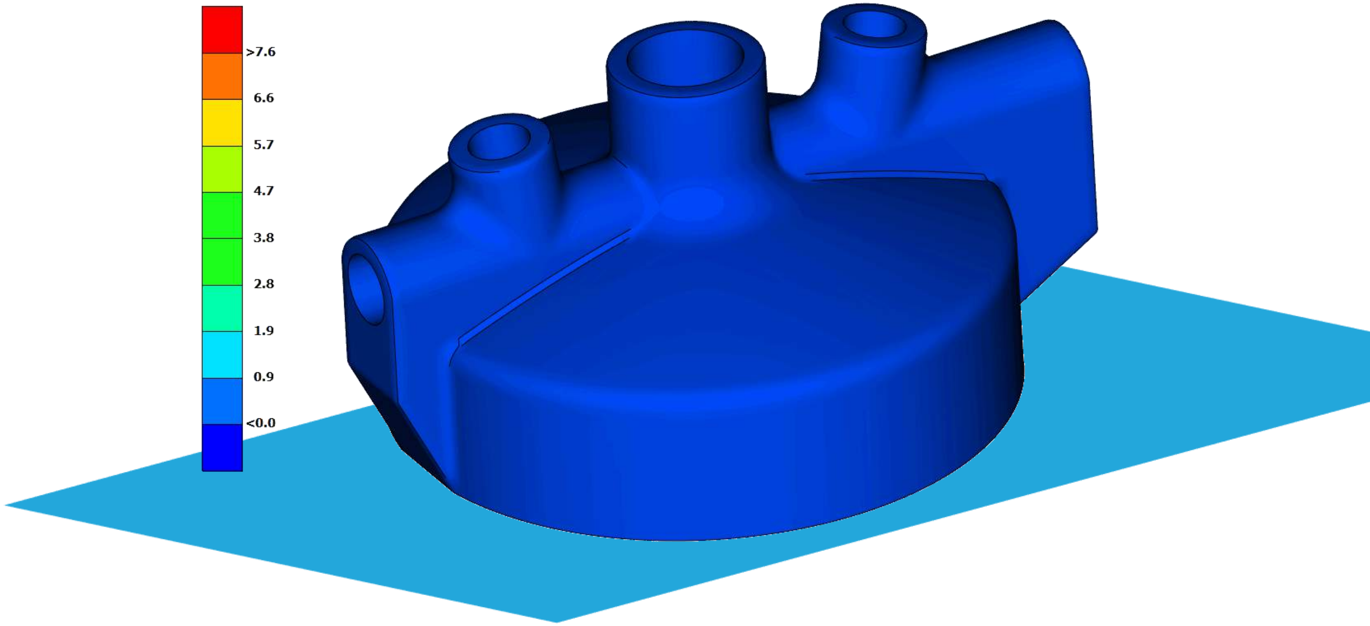
- Optimal alignment with support structure

D&S

- Reduction of iteration steps through optimization simulation

Sinter Simulation

- **Shrinkage and warpage prediction**
  - During sintering, the part undergoes an anisotropic shrinkage.
  - Some geometrical aspects can lead to warping of the part.
  - Our sinter simulation can predict these effects
    - Reduces time consuming and cost expensive trial-and-error loops.



Simulation of the shrinkage and warpage during sintering

Sinter Simulation

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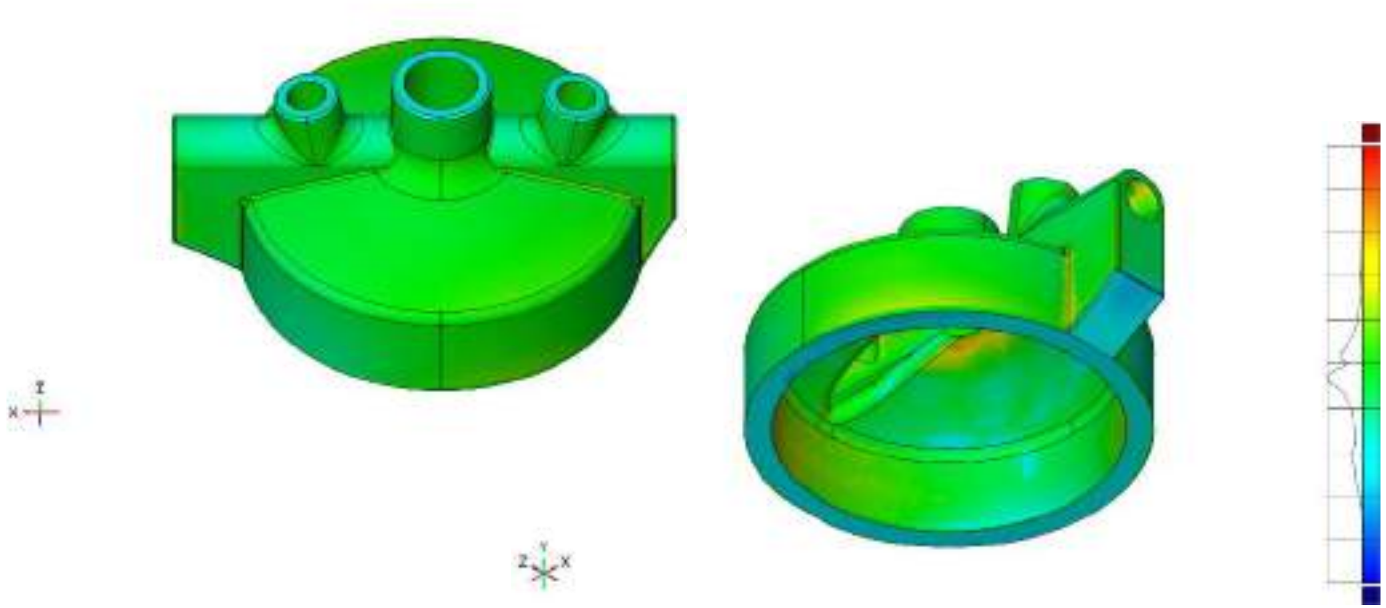

Comparison of sintered part (3d scanned) with the predicted geometry of the sinter simulation

Sinter Simulation: Distortion

- **Sinter Distortion**
  - A greater need for supports is required in D&S than in printing

green part

metal part

- **Raft & Distortion**
  - Rafts can prevent distortion but required extended printing times

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Sinter Simulation: Distortion

- **Shrinkage and warpage prediction**
  - During sintering, the part undergoes an anisotropic shrinkage.
  - Some geometrical aspects can lead to warping of the part.
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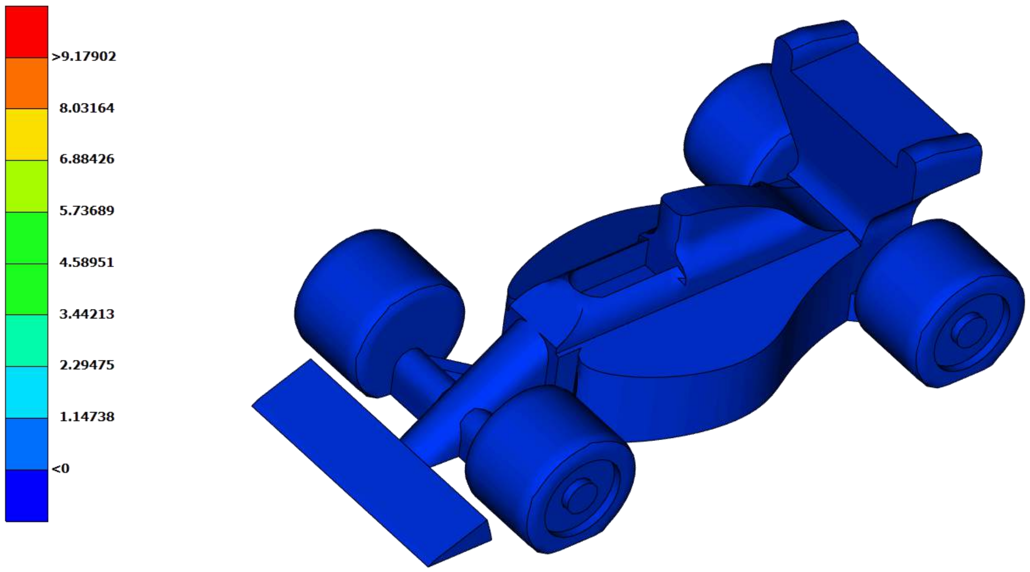
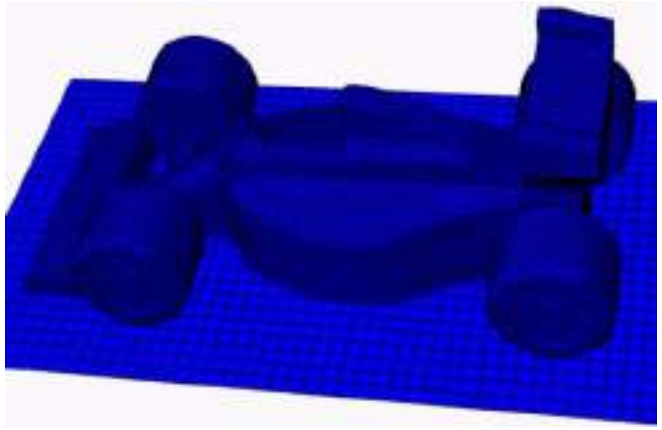


Corrected green part geometry via iterative optimization

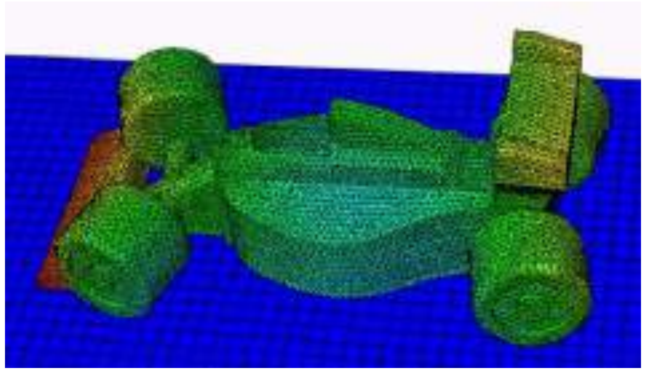
Sinter Simulation: Distortion

Input: STEP-file with initial=final geometry to simulate the part

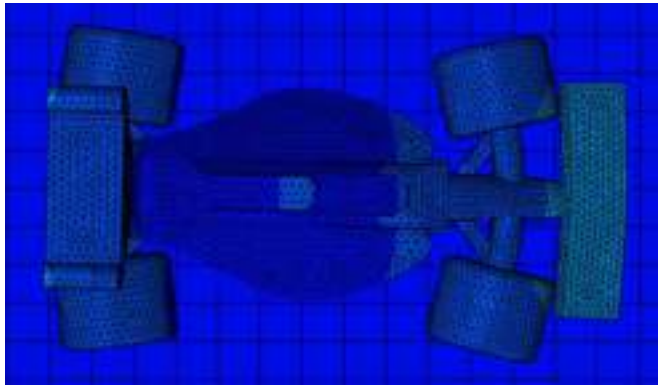
Initial=final geometry



Sintered part

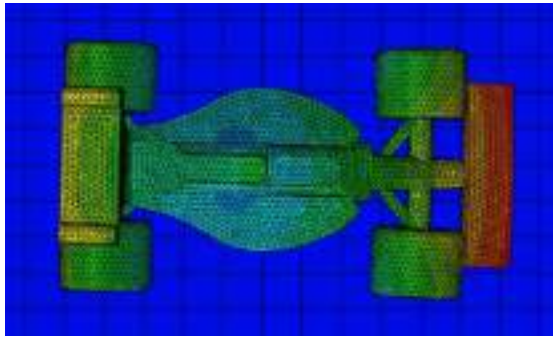


Corrected initial geometry



Output: STL-file for printing to achieve final geometry

Final sintered geometry



Printer, Slicing, & Print Perpetration

Printer Requirements

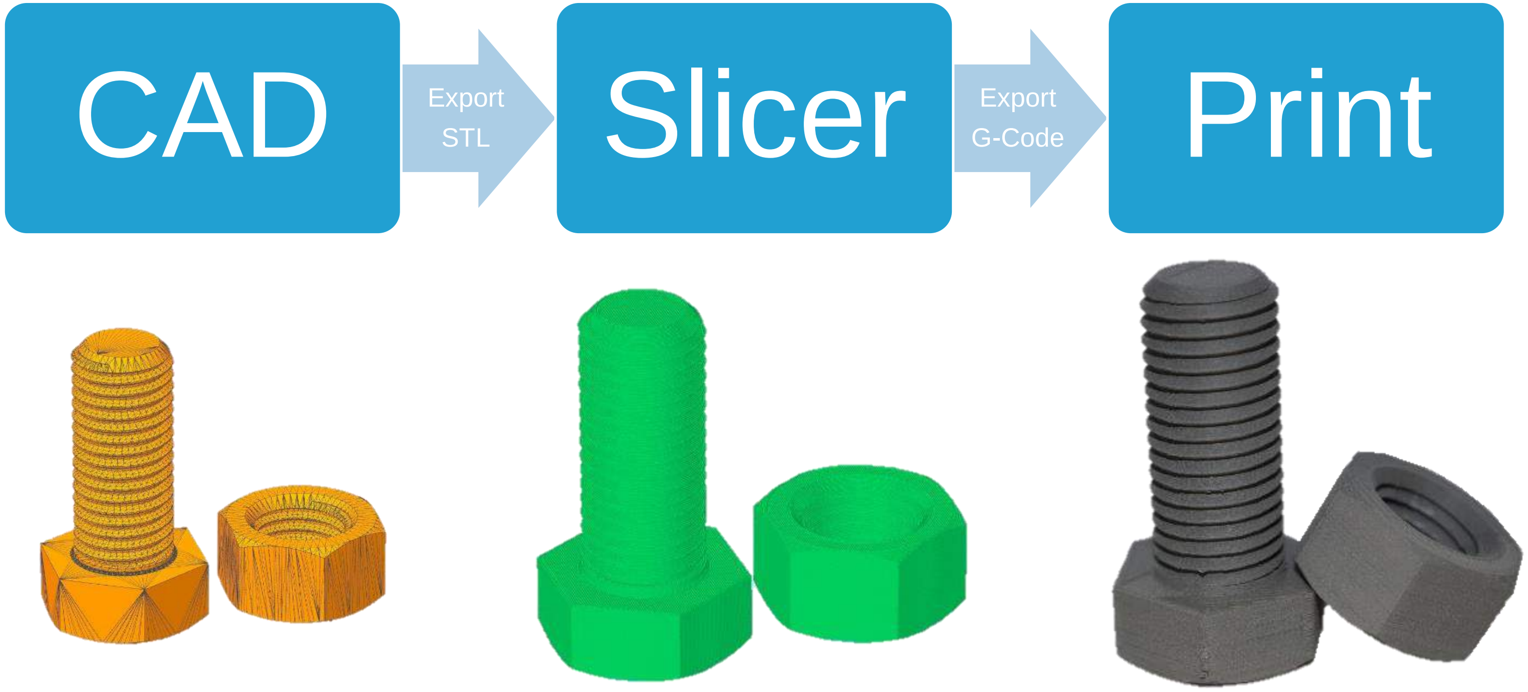
- **Printer**
  - Ultrafuse 316L has been specially designed to be used on most FFF 3D printers
  - There are however minimum requirements for printing

Minimum Printer Requirement
✓ Nozzle temp. up to 250°C
✓ Bed temp. up to 90°C
✓ Enclosed chamber
✓ Low chamber air flow

Recommended Printer Requirements
✓ Nozzle temp. up to 250°C (buffer for temp. stability)
✓ Bed temp. up to 120°C (buffer for temp. stability)
✓ Enclosed and heated chamber (in testing phase)
✓ Dual extrusion print head

Slicing Introduction

- A solid model is imported into the slicer (STL, 3MF, etc.)
- Enables scaling of the model
- Separates a solid model into layers
- Creates "Go Codes" for the 3D printer to produce each layer of the part in sequence
- Generates support material in either automatic or manual process
- Print preview enables visualization of the printing process

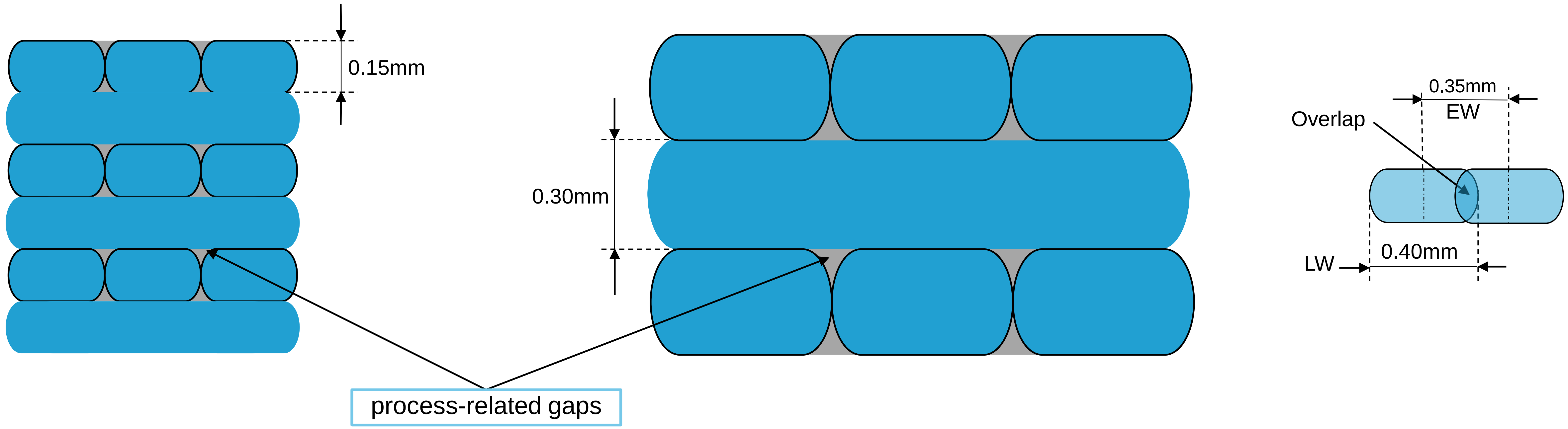


Recommended Printer Process Parameters

Parameter	Recommended	Comment
Nozzle size	0.40 mm	Influenced the print quality (details) and print time; stainless steel or hardened nozzle!
Extrusion Multiplier	1.0 – 1.20	Should be checked; dependent on the printer
Extrusion width	0.35 mm	Dependent on the nozzle size
Retraction distance (direct/ Bowden)	1.5 mm / 5.0 mm	Direct / Bowden extruder
Retraction speed	45mm/s	Recommended
Layer height	0.15	Range 0.10 – 0.25 mm (resolution)
Outlines	1 (2)	Dependent of the part and print quality; overlapping between the outlines must be sufficient
Infill %	100%	Less than 100% for hollow parts
Infill type	Min. 60%	- Rectilinear (100%infill); - Honeycomb or grid (less 100% infill)
Outline overlap %	35%	Should be checked; dependent on the printer
Infill extrusion width	100%	100% recommended!
Nozzle Temperature	235 - *250°C	Actual temperature/ *max. Temp. Cause of POM
Bed temperature	90 - 120°C	Actual temperature
Cooling	No part cooling	Part cooling increases warpage and delamination
Default print speed	35 mm/s	Printing speeds in regard of part complexity and size

Layer Height & Extrusion Width

- **Layer Height, Extrusion Width, & Stability**
  - Improper layer height and extrusion combination can create gaps that can decreased stability in debinding and sintering
  - **Hypothesis:** Smaller gaps are more easily closed by sintering than larger ones [1]



[1]: Diploma thesis by Konstantin Belasik “Investigation of strength-related parameters on fused layer modeling metal parts made of metal composite filament using design of experiments“

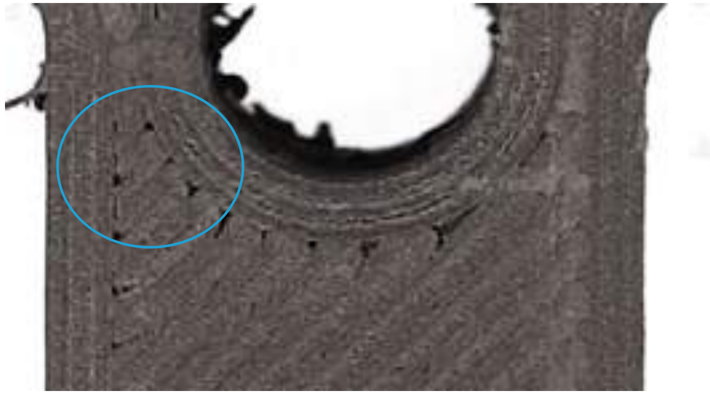
Nozzle Temp & Cooling

- Low nozzle temperatures can prevent layer adhesion
- No part cooling: reduced warpage and delamination

Outlines & Overlap

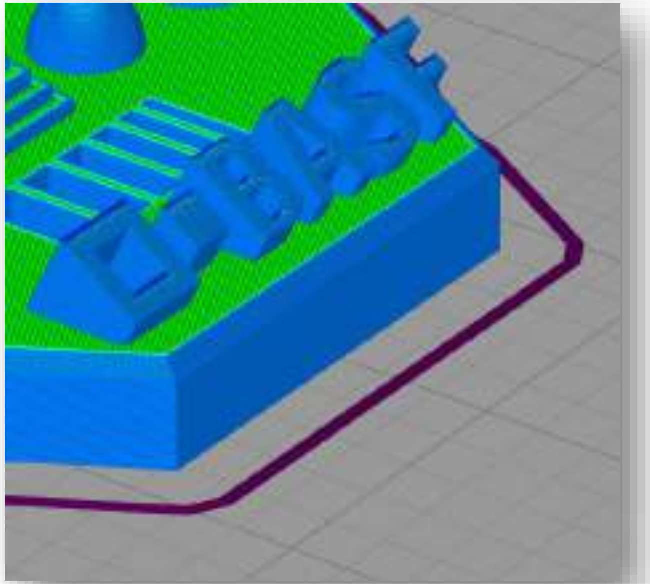
- **Outlines**
  - 1 Outline is usually sufficient; too high and you risk collapse
    - Ensure proper extrusion width
  - Improved surface quality observed

- **Infill Outline Overlap**
  - Overlap values greater than 30% typically achieve the desired part density
    - Values greater than 60% can reduce surface quality

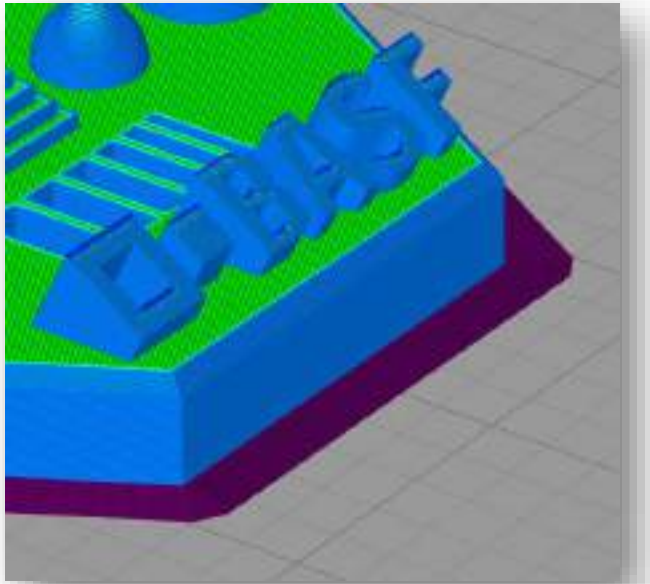


Additions & Build Plate Adhesion

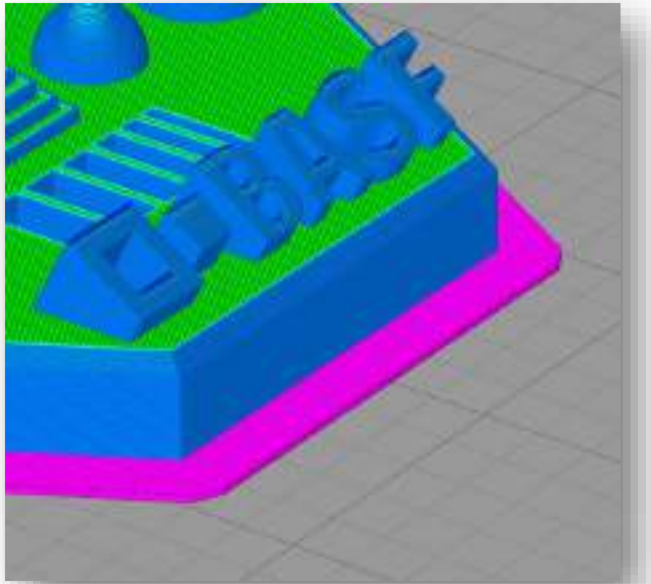
- **Additions**
  - **Skirt:** Mainly to prime the nozzle, if no Brim of Raft is used
  - **Brim:** By experiencing corner warping or similar
  - **Raft:** Creates a bottom surface the print can adhere to
- Recommend to use Polyimide foil (0.15mm thick) or dimafix© glue stick



Skirt



Brim



Raft

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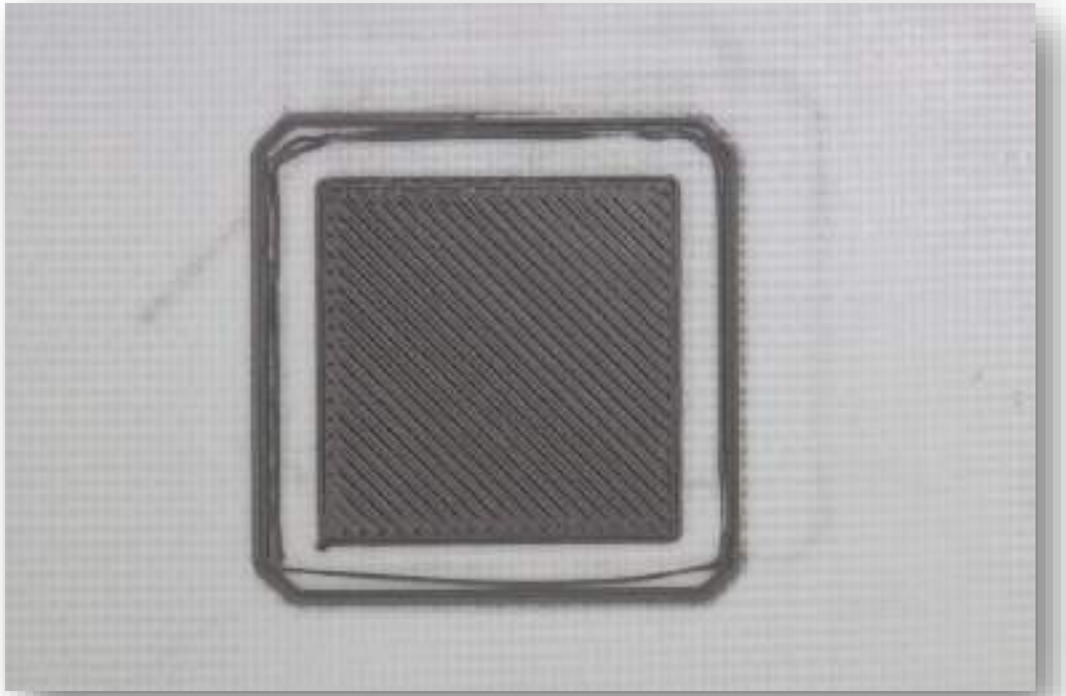
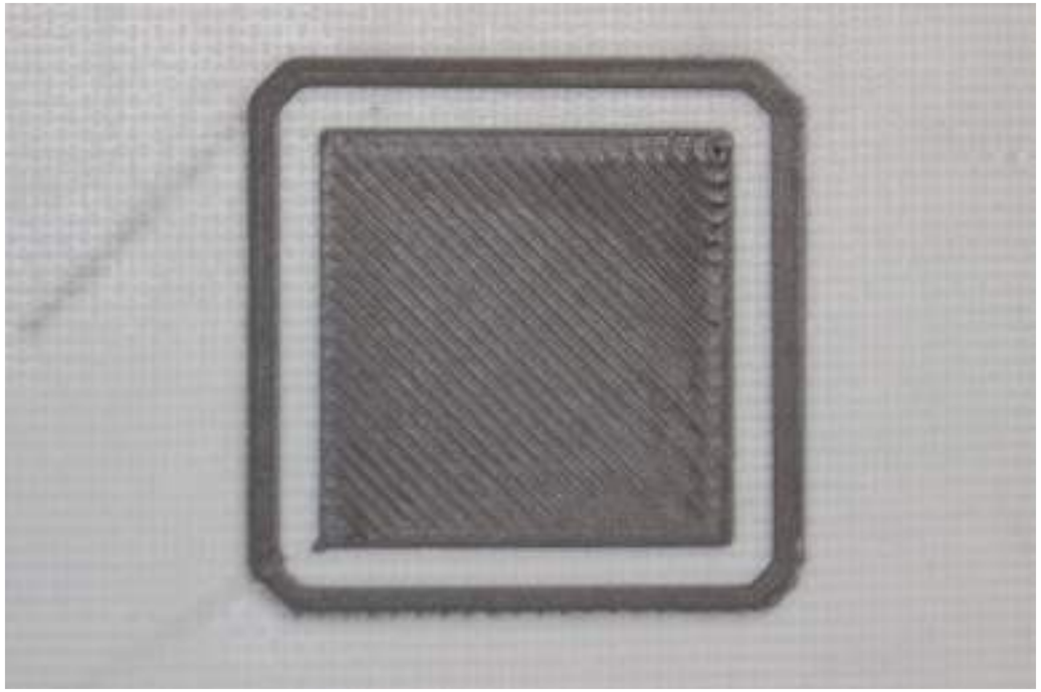
Printer Calibration

First Layer

- First layer is crucial for a successful print
- Bad adhesion will not prevent warpage during printing
- The layer segments should be uniform an connected to the build surface



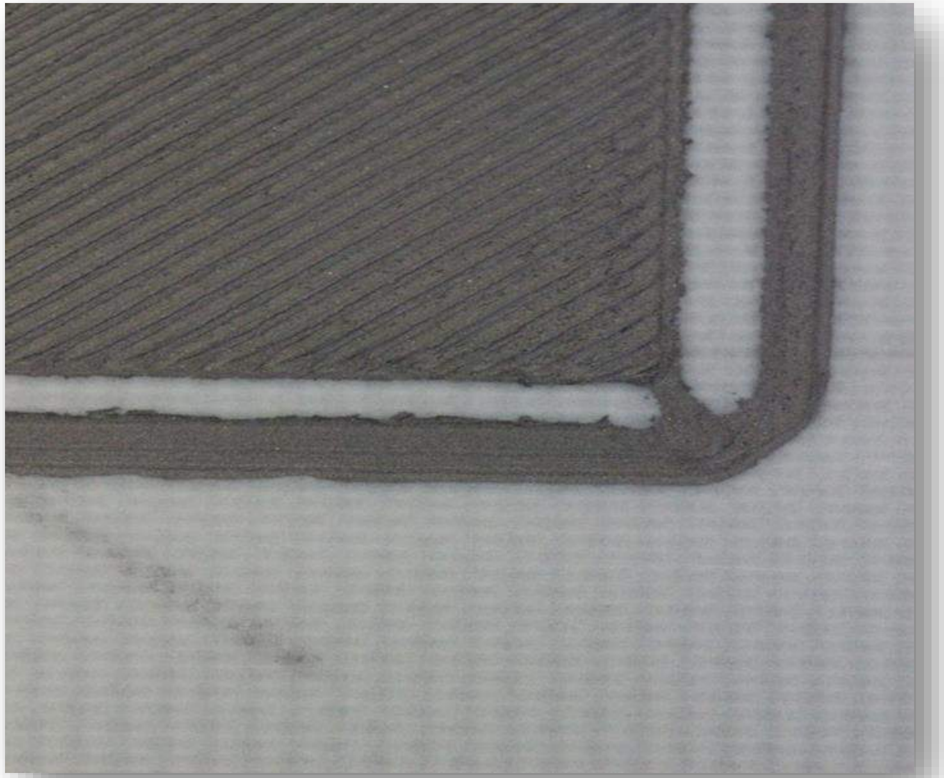
Nozzle too far away from the print bed



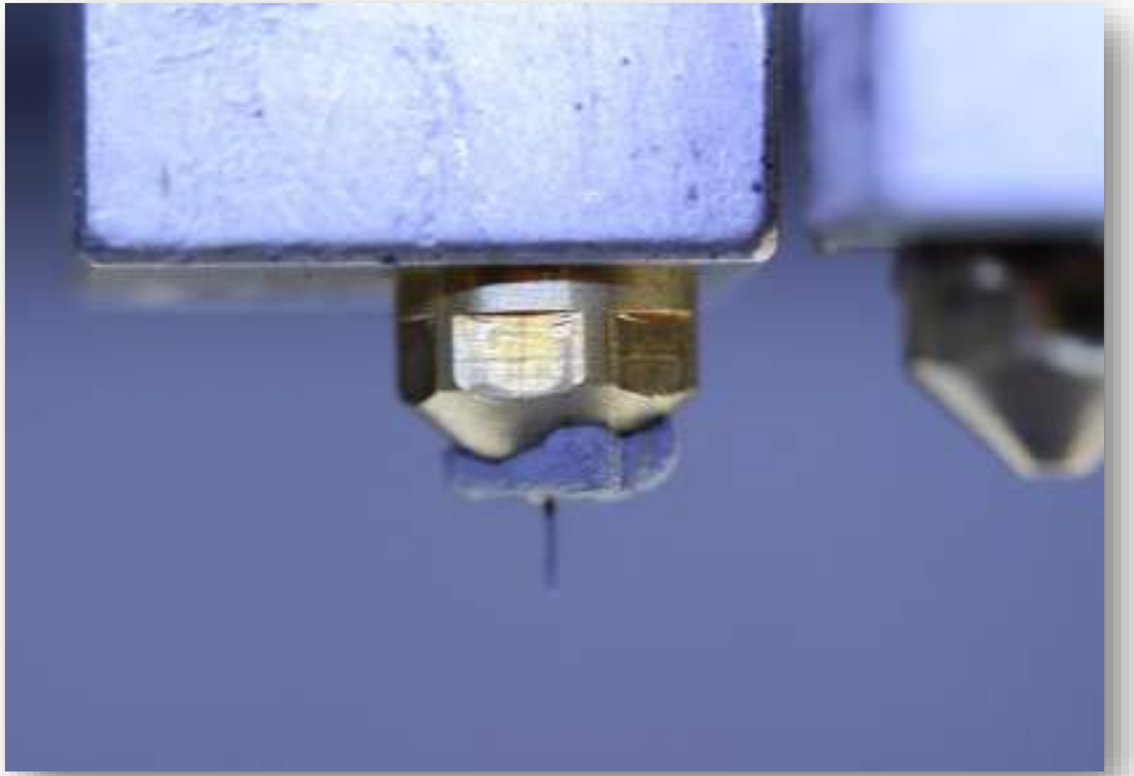
Correctly printed first layer

First Layer

- If the first layer is not right adhesion will not be great enough to prevent warpage during printing



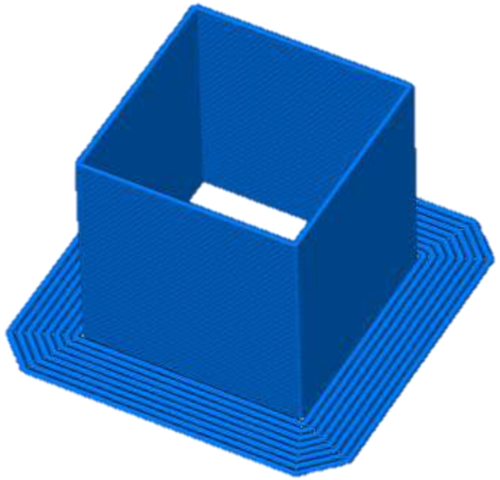
The extrudate swells, the layer is heavily smeared and uneven



By smearing the extrudate collects at the nozzle, which can lead to nozzle blockage

Single Walled Tower

- **Testing & Calibration of Extrusion Multiplier**
  - Each material has different viscosity.
    - This effects the size of the extruded material
  - Average wall thickness should be higher than extrusion width

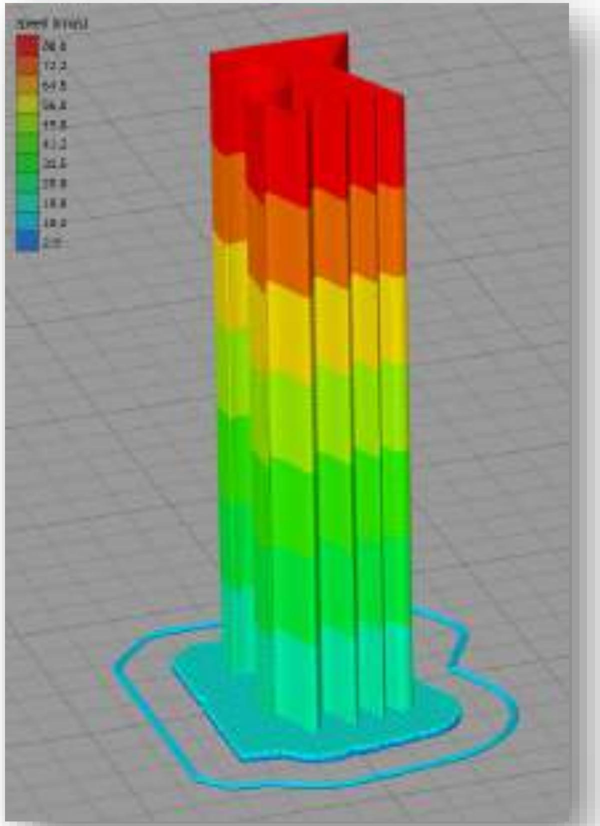


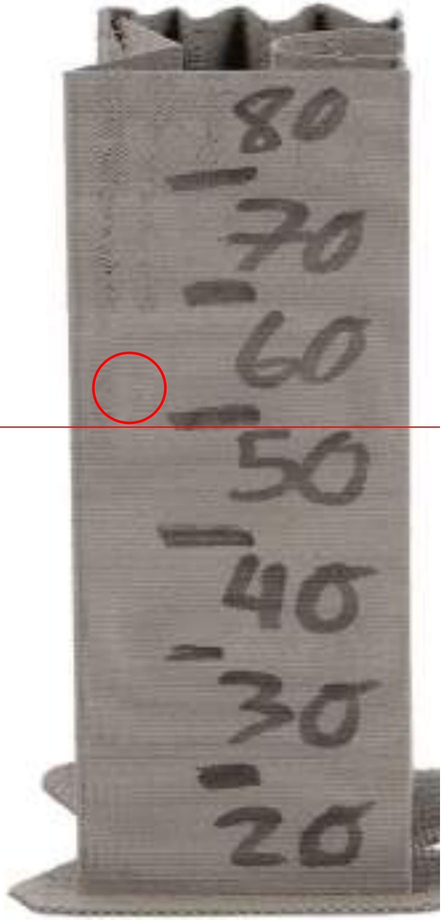
- **Procedure**

- Measure the wall thickness of the cube (front first and then clockwise)
- 0.38 mm (front), 0.37 mm (left), 0.37 mm (back), 0.39 mm (right)
  - = Ø 0,3775 mm Under Extrusion
- Target value / real value = new extrusion multiplier
  - 0.4 mm / 0,3775 mm = 1,059 = 1,06

Speed Tower

- This test is used to tune the appropriate speed at the designated extrusion multiplier

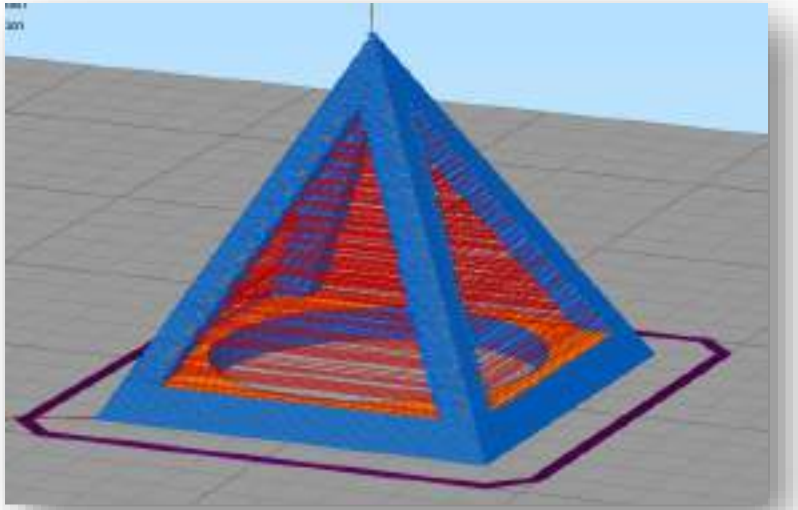




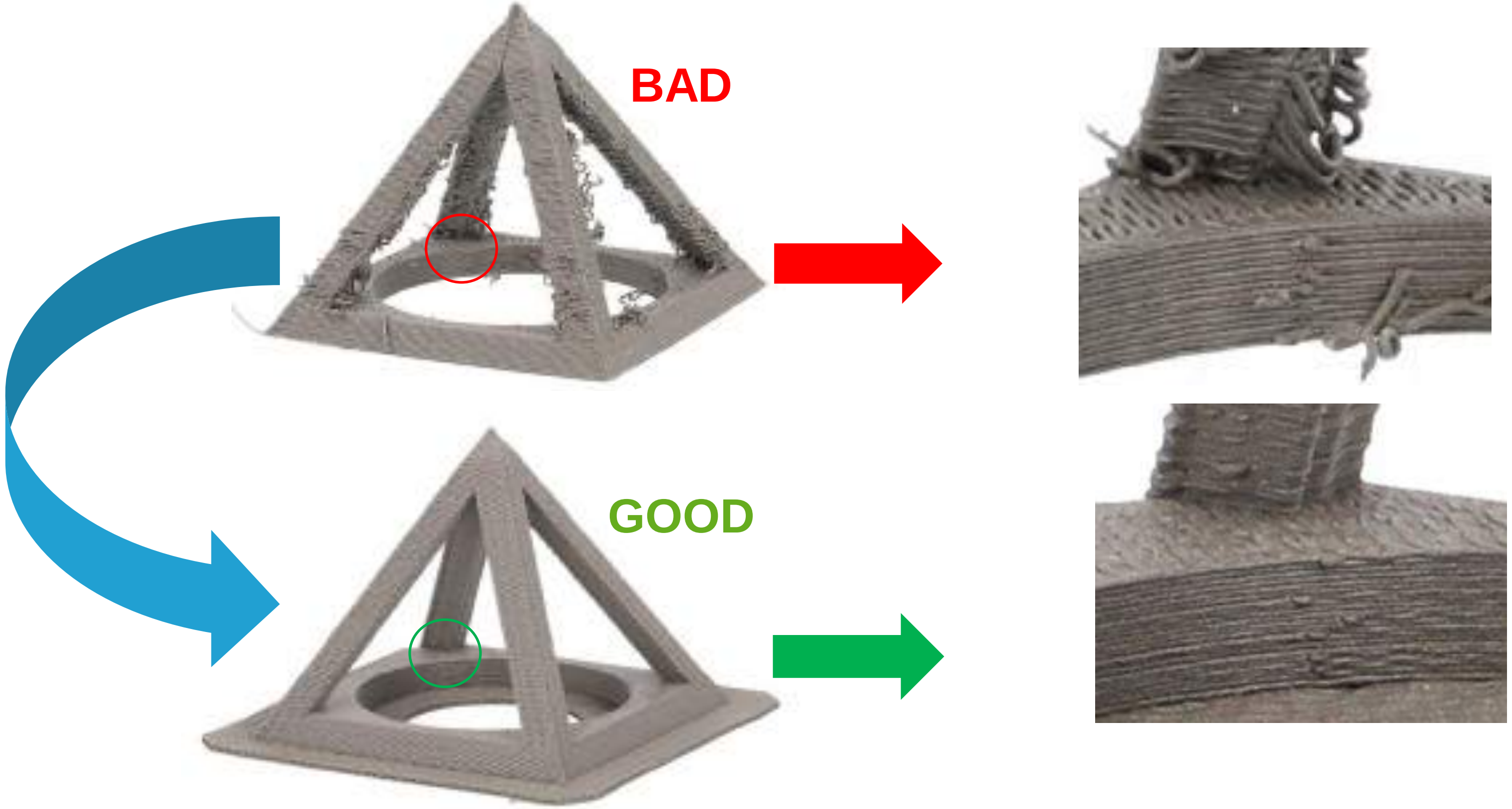
Max. print speed
50 mm/s!

Stringing

- To avoid strings between part features or other parts on the build surface
  - Bad surface quality influences the D&S stability (notch effect)



Test Geometry



Dimensional Accuracy

- **Printing Accuracy & Tolerance Test**
  - Accuracy of the printer
  - To check if that the printer is printing the correct dimension
  - the manufacturing inaccuracy should be known as this should be included in the shrinkage calculation
    - Example Cube:

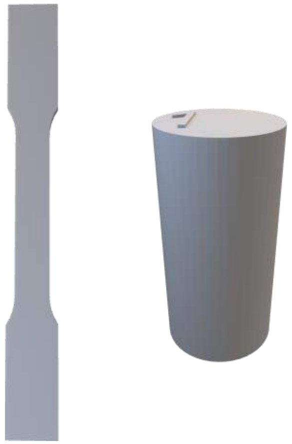
	Part dimension (mm) CAD	Shrinkage %	Scale (typical)	Green Part Should be (mm)	Printed part (green)	Sintered part	New scale
X	20.00	16.5	1.20	24	24.25	20,33	**1.198**
Y	20.00	16.5	1.20	24	24.25	20.25	**1.198**
Z	20.00	20.7	1.26	25.20	25.10	19.90	**1.266**

First layer height!

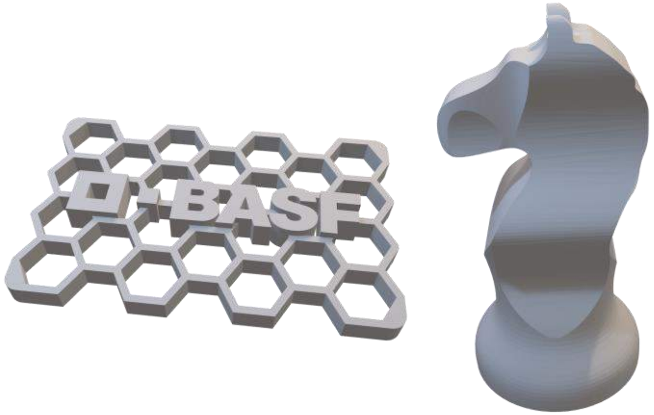
Benchmark Protocol

Benchmark Set Part Summary

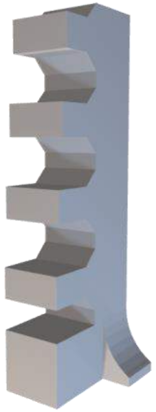
- 5 part types to evaluate the effect of various tools and processes within the Ultrafuse 316L workflow.
- Once printed, green parts sent to BASF 3DPS for processing and evaluation



- Mechanical Properties
  - Tensile strength
  - Elongation at break
  - Density



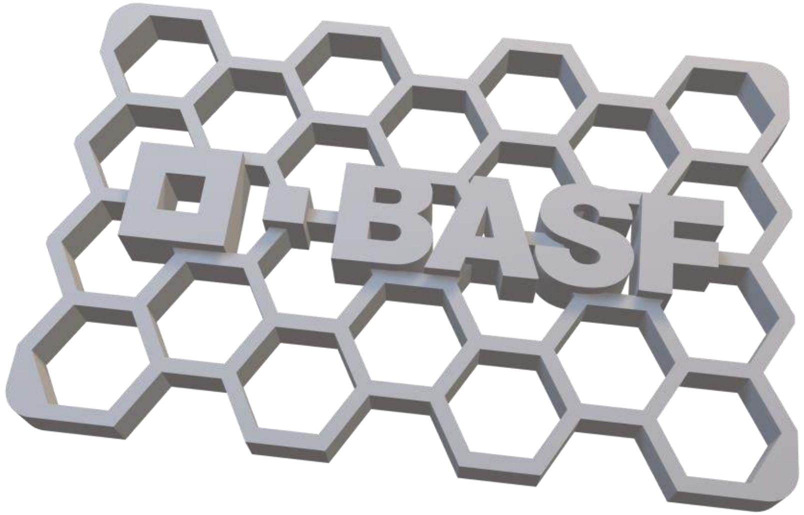
- Unique Value Propositions
  - True hollow structures
  - Design freedom

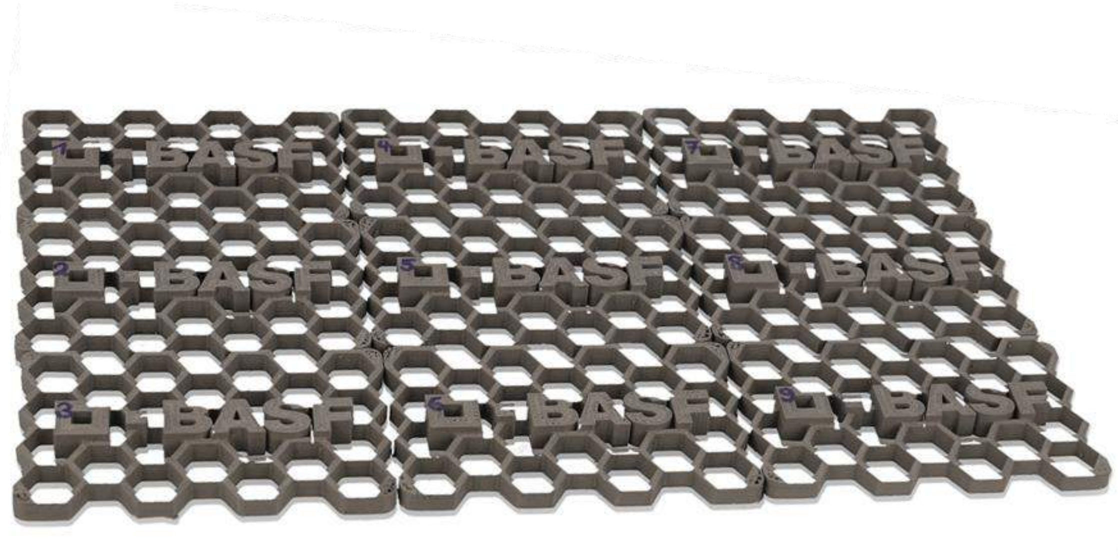


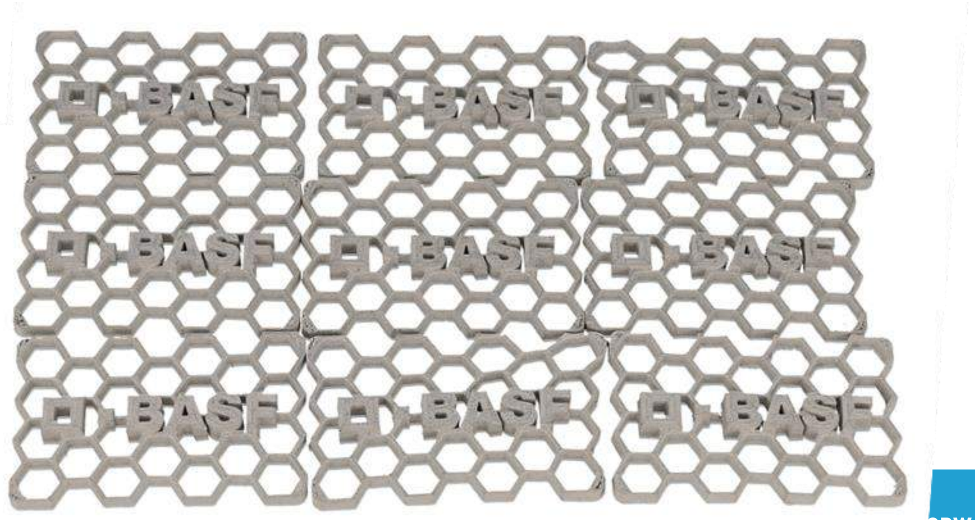
- Design Limitations
  - Sinter stability
  - Distortion

Logo: General Setup

- **Goal:** Visual Appearance
- **Measurements:** Mass & XYZ
- **Quantity:** 9
- No scaling required

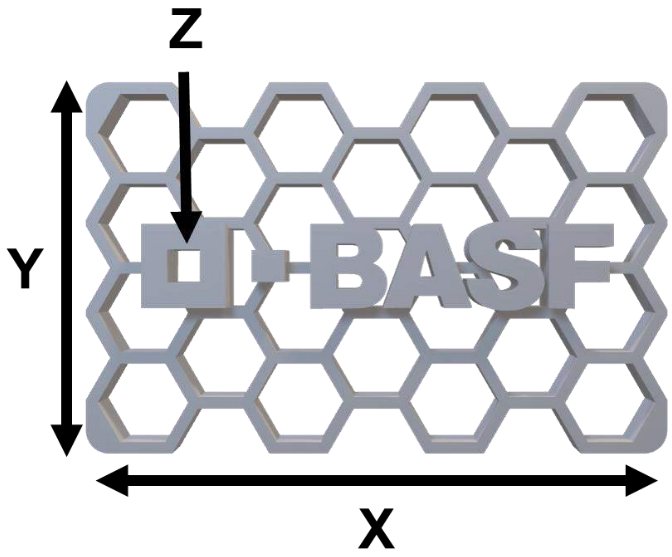


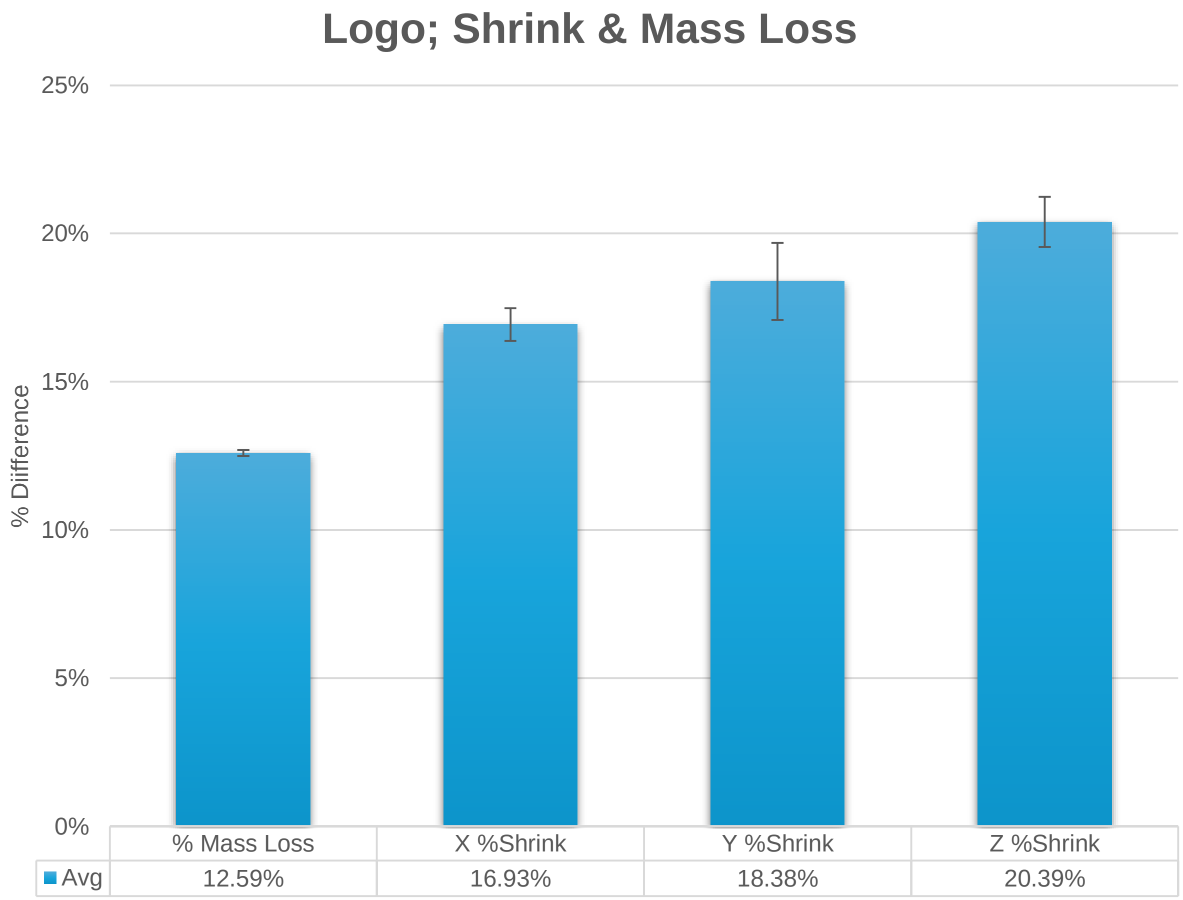




Logo: Shrinkage & Mass Loss

- **Percent Mass Loss**
  - Mass Loss $\equiv \left(\frac{Sintered - Green}{Sintered}\right) \times 100\%$
- **Percent Shrinkage**
  - Shrinkage $\equiv \left(\frac{green - sintered}{green}\right) \times 100\%$





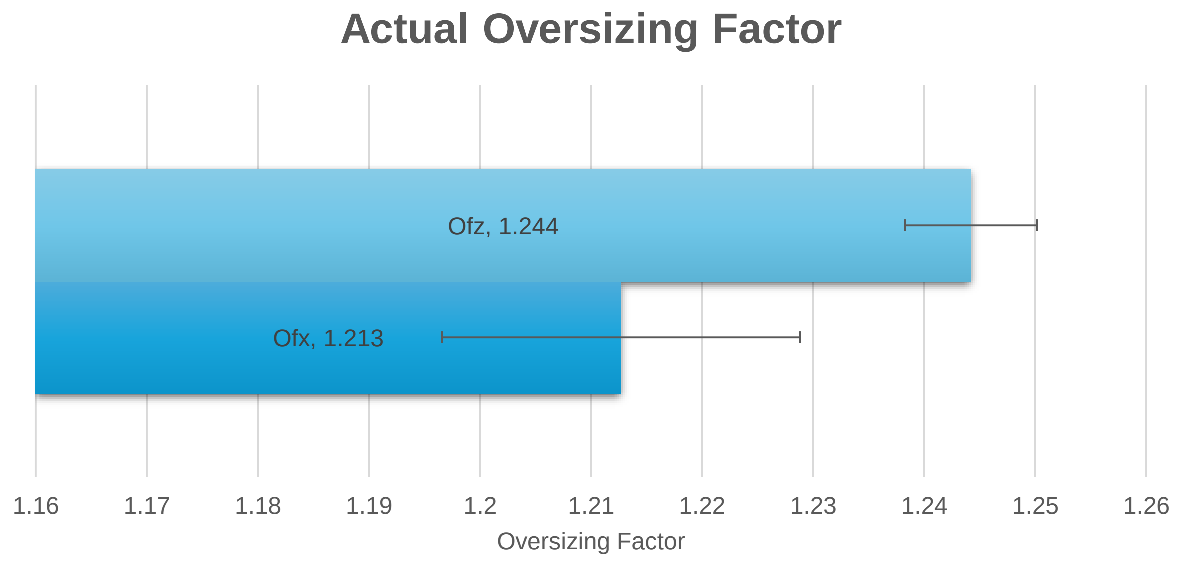
Chess Knight: General Setup

- **Goals:**
  - Minimum mass
  - Visual Appearance
    - Non-100% infill
- **Measurements**: Mass & XYZ
- **Quantity:** 6 (1 of each model)
- No scaling required

Chess Knight: Minimum Mass & Shrinkage

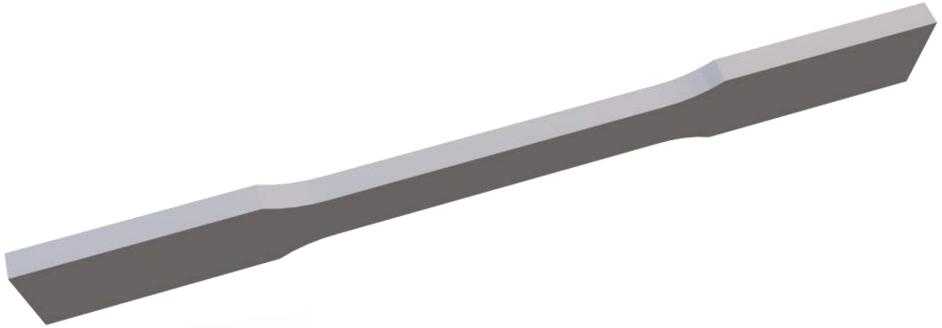
- **Minimum Mass**
  - The challenge for this part is produce the lightest part
  - Geometric accuracy must be maintained
  - Shrinkage magnitudes will change with infill density

- **Oversizing Factor:**
  - $Of_x \equiv \left(\frac{X_{green}}{X_{sintered}}\right)$
  - Corrected oversizing factors can be used to increase accuracy



Tensile Bar: General Setup

- **Goal:** Optimal tensile strength
- **Type:** DIN 50125 E3 x 8 x 30
- **Quantity:** 10
- No scaling required



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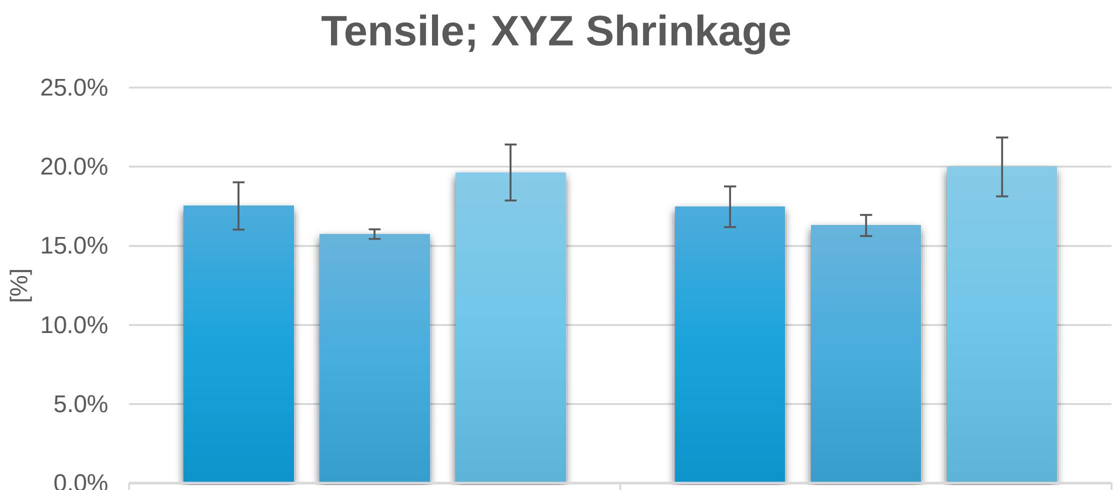
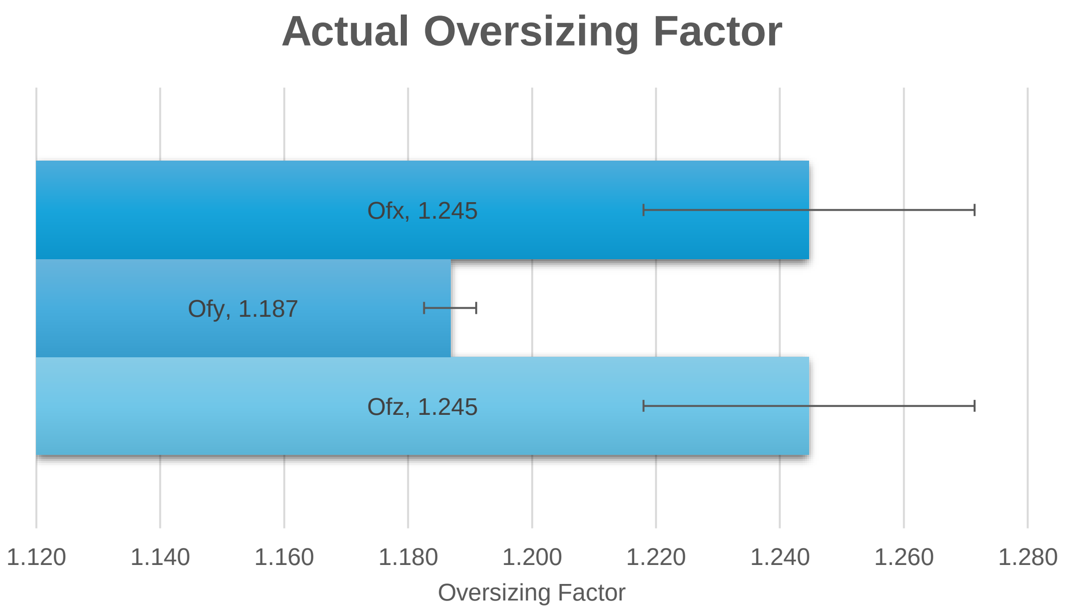
Tensile Bar: Shrinkage & Scaling

- **% Shrinkage:**
  - Values within typical range
  - X/Y difference due to friction under shrinkage

- **Oversizing Factor:**
  - Corrected oversizing values
    - (scaling factors)



	Submission	Population
Sx%	17.52%	17.48%
Sy%	15.74%	16.28%
Sz%	19.63%	19.98%



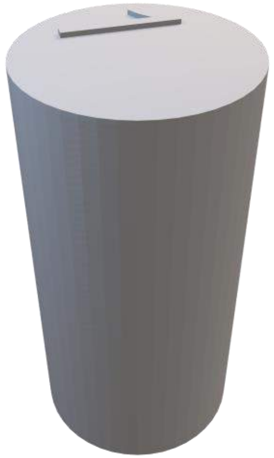
Kragarme / Sinter Stability: General Setup

- **Goal:** Sinter stability equals the length of the longest surviving arm
- **Measurements:** Mass, XYZ, Survival
- **Quantity:** 5
- Printed in flat orientation / Sintered Standing
- No scaling required

Kragarm Score

Cylinders: General Setup

- **Goal:** Maximum Density
  - Max Theoretical Density = 7.97323 (g/cm^3)
    - CNC machined 1.4404 wrought cylinders
- **Measurements:** Mass, XYZ, & Density
- **Quantity:** 4 (1 of each model)
- No scaling required



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