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Innovating Additive Manufacturing

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We create chemistry

Ultrafuse® Metal Filaments

User Guidelines for 3D Printing Metal Parts

> “A great part starts with great design”

Find out more about our metal filaments

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Introduction

1

Ultrafuse metal filaments are metal-polymer composite filaments specifically designed for Fused Filament Fabrication (FFF) printing. By utilizing FFF 3D printing, initial machine investments can be orders of magnitude more affordable and much easier for those wishing to take advantage of metal 3D printing.

Possessing high flexibility, Ultrafuse metal filaments are ideally suited to complex idler pulley and guide roller filament transportation systems found in the wide variety of FFF platforms, from hobby to advanced industrial machines. The non-slip outer surface of Ultrafuse filaments have been optimized for printing on both Bowden and direct drive FFF extruders.

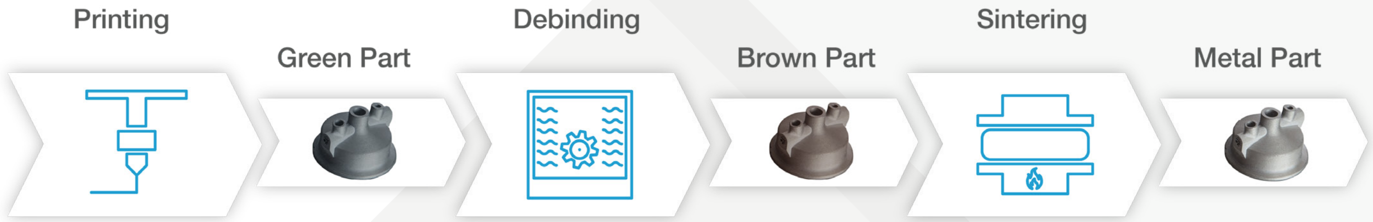
High metal contents in the mid 90% by volume combined with an even distribution of metal powder within the binder matrix, Ultrafuse metal filaments provide dependable performance and help to reduce the risk of printing defects to increase final part success rates.

Compared to other fine metal powders methods like Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Direct Metal Deposition (DMD) and Binder Jetting, Ultrafuse filaments bind metal particles within a robust polymer system at high density to reduce potentially harmful fine metal particle exposure. Additionally, because there is no need to unpack printed parts out of raw powder within the build chamber, operators have minimal exposure to fine metallic particles.

2

Process Workflow “From Art to Part”

Printing with an Ultrafuse® Metal Filament is very similar to plastic FFF printing, however; there are subsequent processing steps that dictate the specific practices to increase the probability of successfully producing a full metal part. Once filament is loaded, flow has been calibrated, and the desired parts have been sliced, printing can begin.



2.1 Debinding & Sintering (D&S)

The polymer binder system is removed in a controlled industrial process known as catalytic debinding to produce the “brown part”. After the removal of primary binders, brown parts generally possess lower strength than the green part but remain dimensionally stable.

Sintering is then used to combine that the metal particles of the brown part and form a solid mass by heat without fully melting to preserve part shape. Once sintering is complete the full metal part is ready for use or can be further processed via traditional metal working methods.

2.2 Minimum Printer Requirements

It is possible to print Ultrafuse metal filaments with a standard desktop FFF printer, however; the chosen machine and its condition can dramatically influence part accuracy and quality. Similar to traditional FFF materials like ABS, high warpage can occur with temperature variations and it is therefore recommended to fully enclose the printing chamber to limit air flow. Printing stability can in some situations benefit from actively heated chambers but are not essential.

2.2.1 Nozzles

It is recommended to use new clean nozzles when preparing your printer for Ultrafuse metal filament printing. Any excess plastics or residual material in the nozzle can be hazardous to both the printed parts and the debinding and sintering equipment utilized to produce full metal parts.

Due to Ultrafuse metal filament's high level of metal loading, nozzle wear has been observed in excess of traditional plastic filaments. Hardened nozzles have been shown to provide longer usability, however; typical brass FFF nozzles can provide excellent performance if they are replaced on a regular basis. For non-hardened nozzles replacement is recommended after printing of every 3kg / 1 full spool.

2.2.2 Spool Holder

At 3Kg (6.6lbs) supplying material from a full spool can be difficult for some printers and can result in under extrusion and other flow issues. Therefore, a spool holder using bearings or other techniques of reducing the required force to deploy filament is recommended. Any number of DIY or commercial options, like the Polymaker PolyBox, have been proven effective.

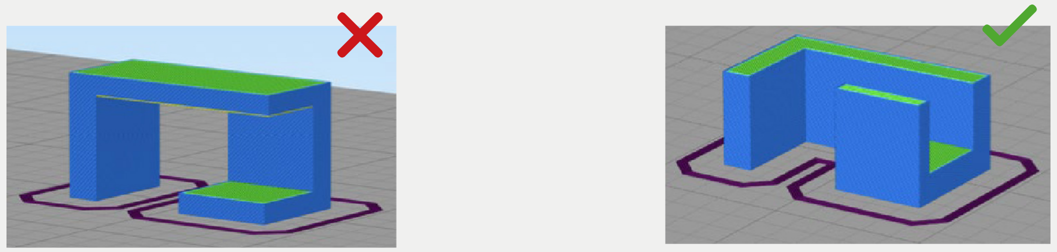
3

Slicing

FFF is a manufacturing method in which material is deposited in a series of 2D layers. Multiple layers are stacked on top of each other to create a 3D part. The 3D model in .STL format is cut into several layers or "slices" so that movement instructions, required by the printing system, can be created with Computer Aided Manufacturing (CAM) software, commonly referred to in FFF as a slicer.

3.1 Part Orientation

The alignment of a part on the printer's build plate can critically affect the accuracy, strength, print time, and stability or survival during the debinding and sintering processes. In general, parts should be orientated to provide the maximum amount of a part's surface on the build plate, as seen in Figure 2 below, to provide sufficient connection to the print surface during printing and stability during post printing steps.


Not good, support needed.

Good, no support needed.

Figure 2 Part Orientation Example

3.2 Suggested Printing Parameters

The selection of printing parameters during the slicing process is critical for part quality and printing time. Calibration for the exact printer used is highly recommended as differences in individual printers and their level of maintenance can have significant effects on part outcomes.

The suggested parameters seen in Table 1 serve as a starting point for new users looking to quickly begin printing. As with any manufacturing process, each part provides it specific challenges and will benefit from tuning and optimization to achieve the highest possible quality.

Table 1: Suggested Initial Printing Parameters

Parameter	Value	Comment
Nozzle size	0.3 - 0.8 mm	Depending on level of detail required and print time
Extrusion width	Nozzle size ±10-20%	100-110% of nozzle size
Retraction distance	1.5mm / 5.0mm	Direct / Bowden extruder
Retraction speed	45 mm/s	Recommended
Layer height	0.10-0.25mm	No more than 60% of the nozzle size recommended
Outlines	1–3	Too many outlines can result in wall separation
Outline overlap %	20–35 %	Overlap between the outlines must be ensured
Infill (Solid Part) %	100% Lines	Rectilinear types have shown to produce highest densities
Infill type (Hollow)	>60% Grid or Triangle	Minimum infill above 60% for best results, but lower values possible with testing
Nozzle temperature	220–245°C	Calibrate to ensure actual temperature matches slicer temperature settings
Bed temperature	90–100°C	Calibrate to ensure actual temperature matches slicer temperature settings
Cooling	None	Part cooling generally increases warpage but can be helpful during bridging
Print Speed	30 mm/s	Slower printing speeds produce denser more accurate results
Scaling	XY 120% Z 126%	See Shrinkage and scaling on

3.3 First Layer

Printing a perfect first layer, is the first step in a successful FFF part. The first layer attaches the part to the build surface; when it fails so will the print job. Warpage during printing often occurs due to a lack of adhesion between the part and build surface resulting in poor part accuracy or potentially total loss of the part during D&S.
A clean and leveled build surface heated to 90-95°C (194-203°F) are recommended. To dramatically reduce first layer separation and warpage at the build surface, approved adhesives may be used. Dimafix or Magigoo Pro Metal are two approved products proven to provide both ease of use and excellent part adhesion.

Even and closed.
No swelling, not too “loose”.

Nozzle is too far away from the print bed. First layer is not closed and thus there is not good adhesion of the first layer to the printing

Nozzle is too close to the print bed. The extrudate swells, and the layer is heavily smeared and uneven.

Figure 3

Table 2 below provides a few first layer key points to assist those new to FFF printing or looking to improve their abilities.

Table 2: First Layer Settings

Printing Parameter	Value	Comment
Extrusion width	90-110%	Depending on print surface and model requirements
Layer height	50-70% Nozzle size	Dependent on nozzle
First Layer print speed	50-70% Print Speed	Excessive first layer printing speeds can increase the chance of warpage

3.4 Build Plate Adhesion / Additions

The addition of extra printed features, not included in the part model, can be added during slicing to increase part adhesion, ensure proper extrusion before part printing starts, and add stability. Figure 4 below provides examples of the three most common additional features:

- Skirt: Used to prime the nozzle and allow time to readjust bed level just before part printing begin
- Brim: Can reduce corner warping and provide increased surface area for thin sections.
- Raft: Creates a large first layer surface that the print can adhere to. This is a common solution to adhesion problems or printing surfaces that are difficult to level.

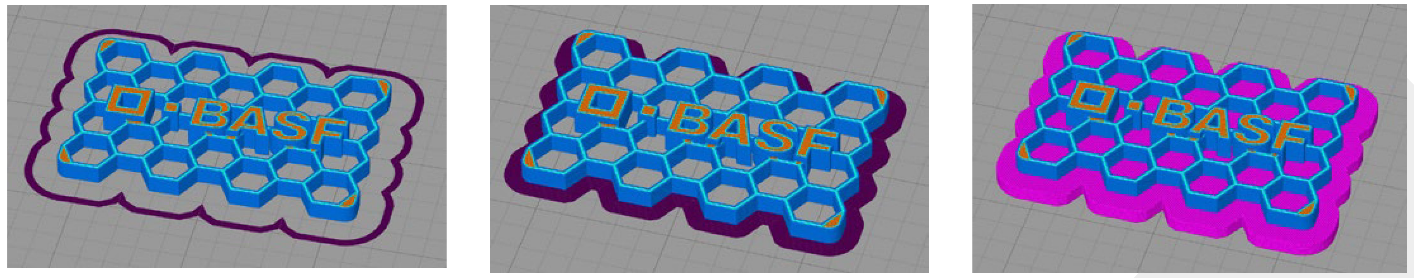


Figure 4 Build Plate Adhesion Additions, (left) Skirt, (middle) Brim, (right) Raft

3.5 Supports “Not Just for Printing”

Ultrafuse metal filament printing requires a greater amount of supports compared to typical plastic FFF. To print an overhanging feature, it is recommended to use supports with overhang angles under 45° as seen in Figure 5 below. During debinding and sintering Ultrafuse metal parts require increased amounts of support to minimize the chance of part collapse or distortion. Support structures have the greatest effect when they are created with full density. The use of support should be minimized during part design to increase stability and minimize the need for post sintering removal of full metal supports.

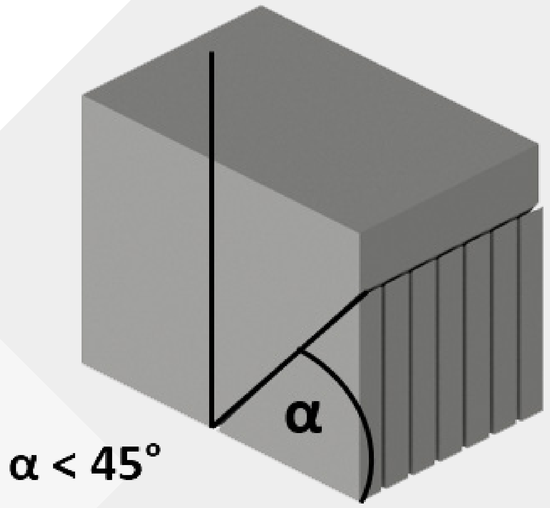


Figure 5: Overhang Angle

4 Debinding & Sintering

The debinding and sintering processes that produce full metal are parts are critical differentiators from typical FFF 3D printing materials. The following is a brief introduction to both processes in order to better understand and optimize your part needs.

4.1.1 Catalytic Debinding (Green to Brown)

Debinding is the removal of binders which are required to enable the printing process. Ultrafuse metal filaments use multiple binder systems to ensure rapid and controlled removal of the binding material. Catalytic debinding is a thermochemical process in which green parts are exposed to gaseous nitric acid (HNO3) in a nitrogen atmosphere and heated. It removes the binder material very rapidly compared to other binding methods (1–2 mm/hr for each external surface). The thicker the part, the longer the debinding time required. Once the polymer-based binder has been removed, the part is referred to as a brown part and is ready to be solidified into a fully metallic part by sintering.

4.1.2 Sintering (Brown to White)

Brown parts are relatively porous and require sintering to produce a solid densified material. Sintering combines the metal particles in the brown part into a solid mass and is carried out under pressures and temperatures below the melting point of the material to maintain the part’s shape.
Sintering in a pure hydrogen atmosphere enables the production of a finished stainless steel component that is almost fully dense. Printing direction and parameters have a large influence on shrinkage magnitudes. Support structures, as with any FFF part, are required when printing overhangs or other horizontal structures. Unlike typical FFF, Ultrafuse metal components require increased support structures to ensure structural integrity throughout the sintering process. Due to its transition from a porous brown part to a dense “white” state, dimensions of the part are reduced. This reduction in size is typically referred to as shrinkage and must be considered during the design phase.

4.1.3 Sintering Will Not “Fix” Cracks

As seen in the gear train part in Figure 6 below, delamination and cracking seen in printing will only be increased during sintering and it is therefore important to only send parts of high quality for processing.

Figure 6: Print Delamination Become Sintered Cracks

Design Guidelines 5

A great part starts with great design. The correct design choices can enable the highest possible quality and performance by exploiting Ultrafuse metal filament’s unique advantages while avoiding potential process limitations. The following guidelines are provided to aid new users in part selection, design, and slicing. Many guidelines are motivated by the needs of the D&S process.
The guidelines are often recommendations not limitations. These guidelines are a living document as we continue to optimize our materials and process knowledge to continuously expand and improve what is possible with Ultrafuse metal filaments.

5.1 Part Size

The maximum green part footprint cannot exceed X 100, Y 100, Z 100 mm in order to fit on the ceramic plates supporting the parts throughout debinding and sintering. If larger parts are required, special arrangements may be made with the D&S equipment provider or processor. Although achievable, larger parts can suffer from warpage while printing and often require longer development times.

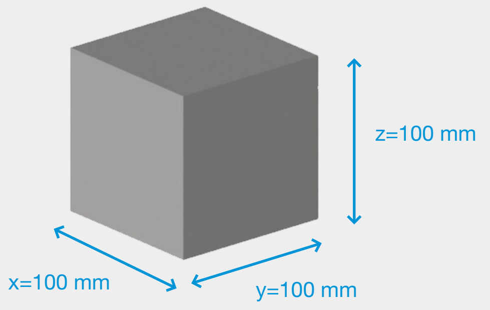


Figure 8: Max Footprint

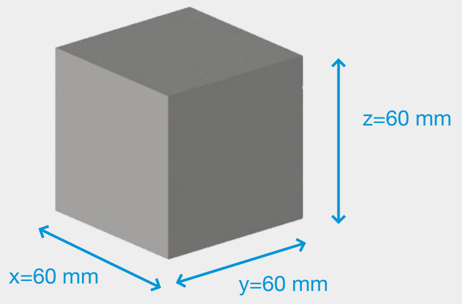


Figure 9: Size for best results

Parts within a 60 mm cube, as seen in Figure 9 above, have proven to be been most successful for new users.

5.2 Shrinkage & Scaling

Part shrinkage occurs as the individual metal particles combine into a solid mass during sintering. The printing Z axis shrinkage is normally slightly greater than X and Y due to the layer-by-layer printing process. Referred to as anisotropic shrinkage, oversizing factors are used to scaleup parts for printing. Oversizing your parts helps to ensure that parts are the correct size after shrinkage.

Printing Axis	Average Shrinkage	Scaling / Oversizing Factor
X & Y	16%	120%
Z		125%

20%

The following is an example of how to determine the correct part oversizing needed in the slicing process.

Shrinkage & Oversizing Factor

Equation & Examples

Catalytic debinding removes the primary binding materials of the filament. Once debound, the part is referred to as “brown”. Brown parts are comprised of tightly packed metal powder. During sintering, the metal particles fuse together, resulting in an overall reduction of the part size.

S = Shrinkage (A measure of the reduction in size from green to sintered) OFS = Oversizing factor (The amount to scale up a green part to produce the desired sintered part)

Typical shrinkage and oversizing factors for metal filaments:

S_x S_y = 0.16 or 16 %
S_z = 0.2 or 20 %

OFS_x OFS_y = 1.20 or 120 %
OFS_z = 1.26 or 126 %

How to convert between shrinkage and oversizing factors:

(eq. 1) $S = 1 - \frac{L_s}{L_g}$ (eq. 2) $OFS = \frac{L_g}{L_s}$ (eq. 3) $OFS = \frac{1}{1-S}$ (eq. 4) $L_g = \frac{L_s}{1-S}$

where:

L_s = the length of the sintered part (in mm) L_g = the length of the green part (in mm)

Example 1

You want to make a 10 mm cube, what should the X, Y, & Z dimensions of the green part be? Using the shrinkage equation 4:

$$L_{gxy} = \frac{L_{sxy}}{1 - S_{xy}} = \frac{10}{1 - 0.165} \qquad L_{gz} = \frac{L_{sz}}{1 - S_z} = \frac{10}{1 - 0.205}$$

L_{gxy} = 11.98 mm L_{gz} = 12.58 mm

Example 2

Scale up the 10 mm cube in your slicer by:

X=120%
Y=120%
Z=126%

Result 1

To obtain a 10 mm sintered cube, the green part needs to be:

X = 12 mm Y = 12 mm Z = 12.6 mm

Result 2

X= 12 mm
Y=12 mm
Z=12.6 mm

5.3 Height to Width Ratio

Height to width ratios under 3:1 have proven to be effective in preventing collapse or distortion during D&S. Ensuring a flat bottom is also critical in reducing possible tilting that can lead to part distortion.

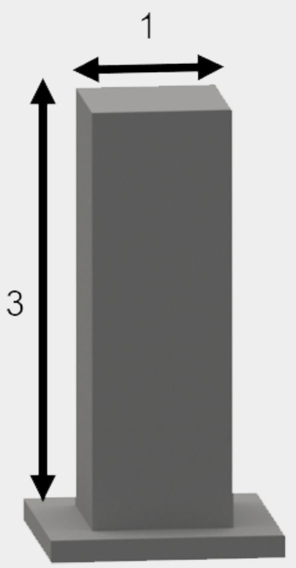


Figure 10; Height to Width Ratio

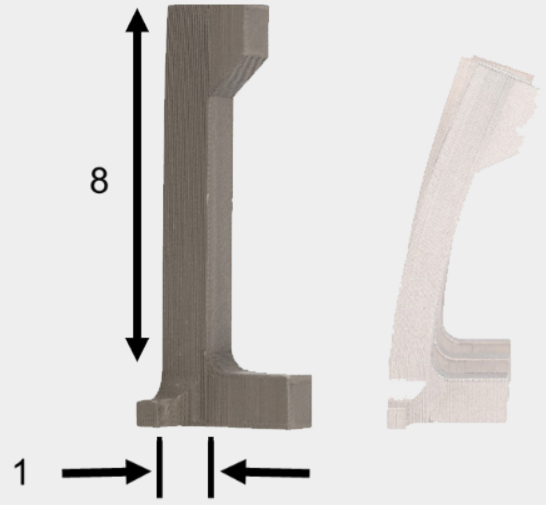


Figure 11: Viscosity Tower Example Parts

Before the metal particles have been fully fused together some features can experience sagging at high temperature. Seen in the viscosity tower example parts in Figure 11 below. With a 8:1 height to width ratio and an overhanging section large distortions occur as seen above.

5.4 Unsupported Walls

To minimize the chance of collapse and distortion, unsupported wall height to width ratios below 6:1, as seen in Figure 12 below, have been proven to be most effective. Although easily printed, as seen in the Figure 13 below, ratios above 6:1 resulted in cracking and even part collapse.

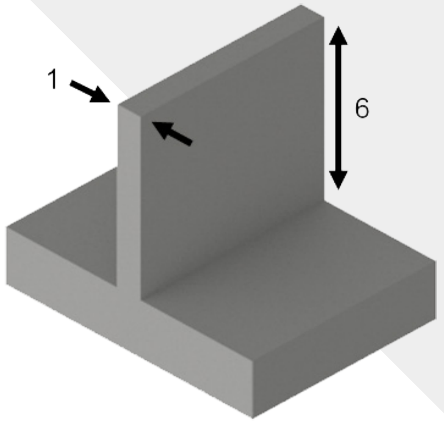


Figure 12: Unsupported Wall

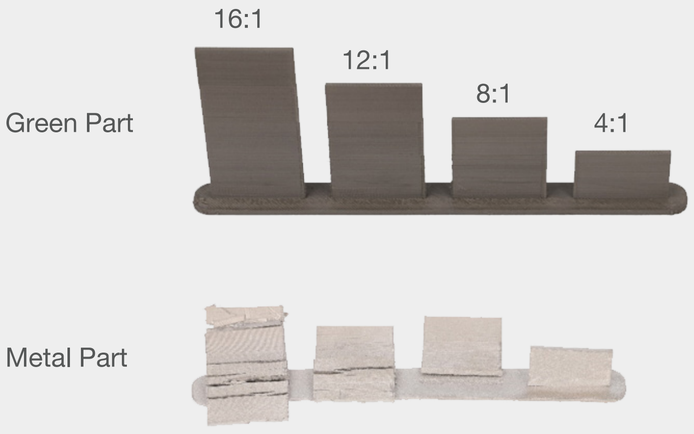


Figure 13: Unsupported Wall Examples

5.5 Flat Bottom

The bottom surfaces of parts must be flat to prevent cracking and the potential for collapse in D&S. Warped bottom surfaces, often resulting from poor print bed adhesion, can cause parts to tilt and distort like the viscosity tower example above, or even collapse in D&S. Sanding bottom surface in such a way as to ensure that parts are as balanced and stable as possible is the easiest method for improving D&S outcomes.

Figure 14: Warped Bottom Can Lead to Failure

Not only taller parts suffer from failures due to not having a truly flat bottom. The spring barrel gear seen in Figure 15 at 100mm in diameter and only 8mm in height is well within a safe height to width and feature thickness, however; warpage from printing was not removed resulting in collapse and cracking.

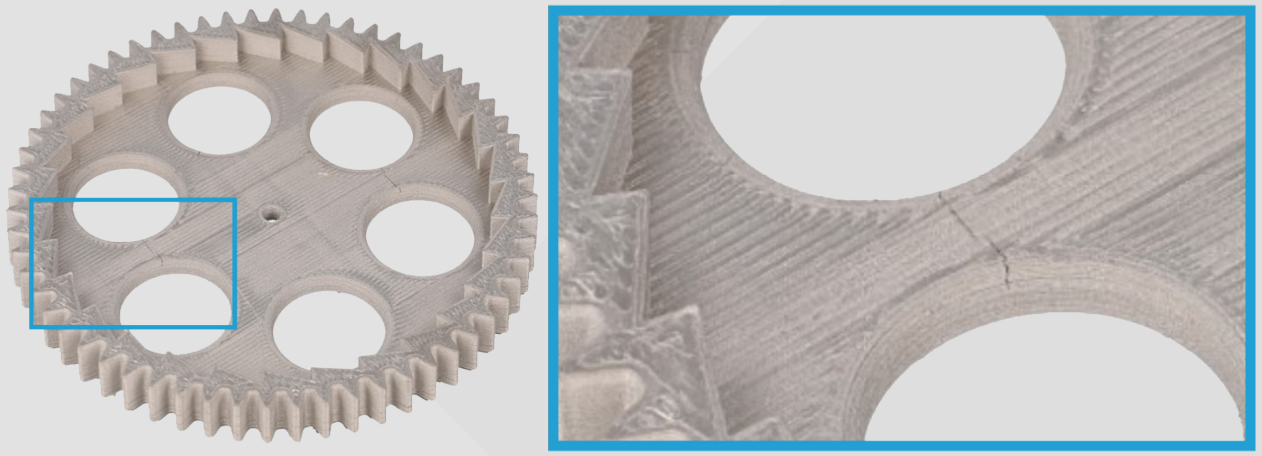


Figure 15: Not Flat & Cracked

5.6 Removal from plate

Caution must be exercised when removing parts from the build surface. Removing a part before it has cooled down can distort the part and even remove bottom layers as seen in Figure 16 below. Due to a poor bottom surface, cracks can often occur on the opposite side of parts as they settle into unsupported areas during sintering.

Figure 16: Damaged Bottom Surface and Resulting Top Cracks

5.7 Circular Features

Circular features are best produced when their axis of rotation is in line with the print direction. Typical FFF printers provide dimensional accuracies of the order of the extrusion width. For an extrusion width of 0.35 mm, typical dimensional accuracies in the XY plane are approximately ±0.35 mm. Layer height is directly related to the accuracy and the level of feature fidelity achievable and is mostly dependent on the printer used. The relation between layer height and dimensional accuracy is most pronounced for circular features in the printing direction (Z-Axis).
It is recommended to rework threaded holes regardless of printing direction or size. The diameter of the hole should be reduced to the diameter of the core hole so that the thread can then be re-tapped.

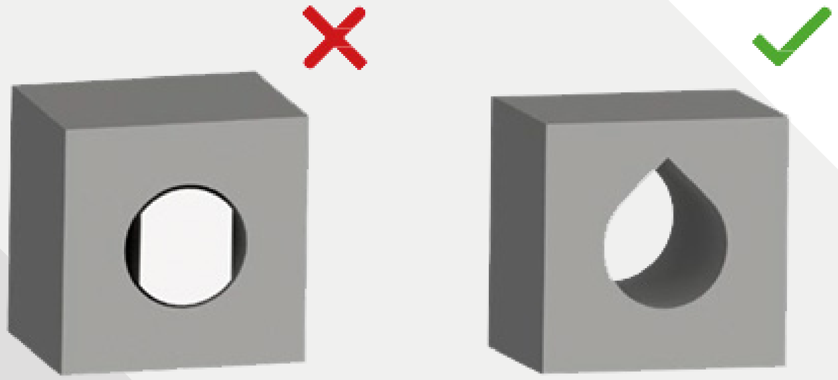


Figure 17: Improved Horizontal Holes

5.8 Wall Thickness

Thin walls should be no less than 1mm in their green state. The thin walls seen in Figure 18 below we printed with inly one extrusion width of 0.4mm and thus suffered major distortion in the sintering process.

Figure 18: 0.4mm Wall Failure

Good adhesion between wall sections is required to minimize wall failures in sintering like that seen in Figure 19 above. When the extrusion width and wall thickness do not match, the inner portions can be left either with no infill or partial infill resulting in a lower density and a reduced structural stability.

5.8.1 Extrusion Width Selection

The width of the material being extruded from the printer's nozzle is referred to as the extrusion width (EW). EW tuning is critical to part accuracy and density. Because most slicers create toolpaths from the outer shell to the part's center, gaps can be formed when the requested EW does not match the feature to be printed. The selection of an appropriate EW must be calibrated prior to printing because it may dramatically affect the material infill and thus the mechanical properties and survival of thin walls.
An example of EW-feature mismatch may be seen in the hexagonal sections seen in Figure 19 below. Proper EW use or part design will produce a fully filled wall of high density and stability.

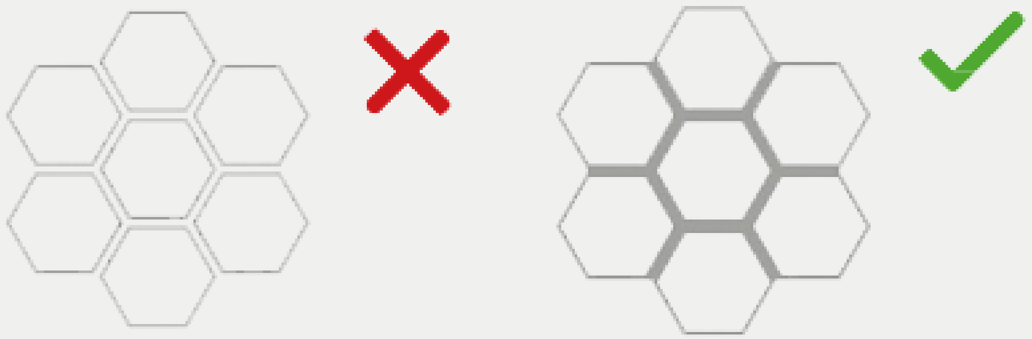


Figure 19: Gap Filling

Scaling must also be considered during design and slicing. Because parts need to be scaled up to account for shrinkage in sintering, designed features may not result in appropriate filling once scaled. Often recalibration or adjustment of EW is the fastest method for adapting an existing printing profile to a specific part's needs.

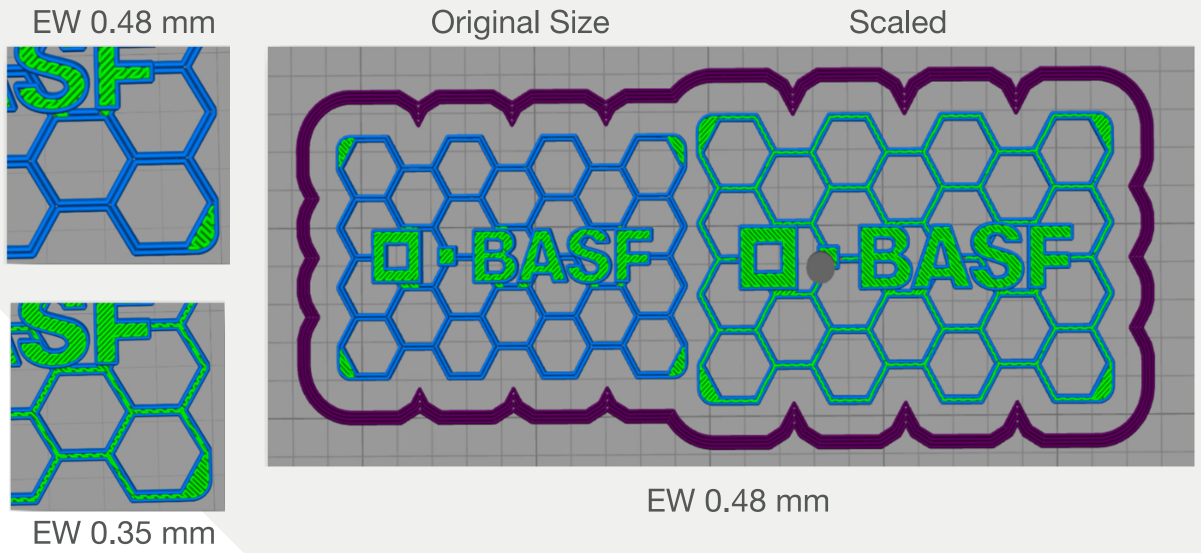


Figure 20: Filling and Scaling

5.9 Infill

Although many parts utilize 100% infill to provide the highest final part density and stability during D&S, dramatic reductions in part mass can be achieved with infill structures. Not possible in most other metal 3D printing methods, FFF's infill structures can create true hollow enclosed part features. Typically, infill under 50% is not recommend without special considerations or adaptations to part design.
A 60% rectilinear infill pattern was used to produce the artistic parts seen in Figure 21 and provided a weight reduction greater than 40% compared to a full density print. Although higher infill amounts tend toward greater first-time success, a dramatic increase in the variety of available infill patterns continue to improve part stability while providing weight saving opportunities.

Figure 21: Mass Reduction Using Infill

5.10 Part Cooling

Although common for many FFF materials, Ultrafuse metal filaments do not require cooling. Using cooling normally results in delamination as seen in Figure 22 below. One exception is the limited use of cooling to enable better bridging results.

Figure 22: Cooling & Delamination Example

5.11 Supports

Print parts as flat as possible and add as much support as possible to increase the survivability of parts during D&S. As with typical FFF part printing, overhangs are a critical concern when using Ultrafuse 316L. During the transition from debinding to sintering, structural stability is at its minimum. Through the strategic use of part orientation and support structures in the printing and post-processing phases, part collapse and deformation can be significantly reduced.
When printing, an overhang angle greater than 45 ° is easily achievable but may suffer from collapse during debinding and sintering if not properly supported. Therefore, additional support structures, not typically required during printing, are necessary to reduce part distortion and to avoid collapse.

5.12 Transition

Thermal stresses during D&S may intensify and exaggerate layer delamination or cracking present in the green part and may be amplified by notches or abrupt cross-sectional changes. The addition of fillets or chamfers, as seen in Figure 23, have been shown to reduce part cracking layer separations. If part geometry constraints limit redesign, the print orientation can often be adapted to reduce geometric distortion.

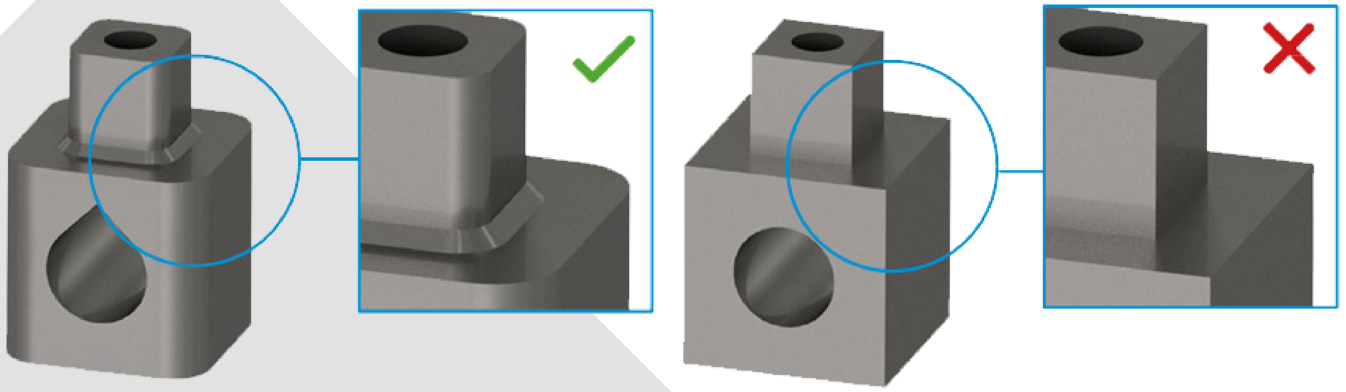


Figure 23: Fillet and Chambers

5.13 Post-Processing

Although, in principle, nearly any geometry imaginable may be produced, post-processing of a sintered metal part may be required to achieve a surface quality or dimensional accuracy greater than that typically achievable with FFF.
Unlike many other metal additive manufacturing processes, Ultrafuse metal green parts are easily smoothed using abrasive or cutting methods. Green state machining, prior to sintering, enables dramatic reductions in machining costs and capital investment due to Ultrafuse filament's high machinability in the green state.
Parts requiring high tolerances may take advantage of traditional metal working methods to produce functional faces. Higher tolerances and surface quality requirements may require further post-processing methods, such as polishing, milling, heat treating, and coating.
The industrial pipe adapter seen in Figure 24 below, was printed and sintered. After sintering, the supports were removed and higher tolerance features were finished, followed by tapping.

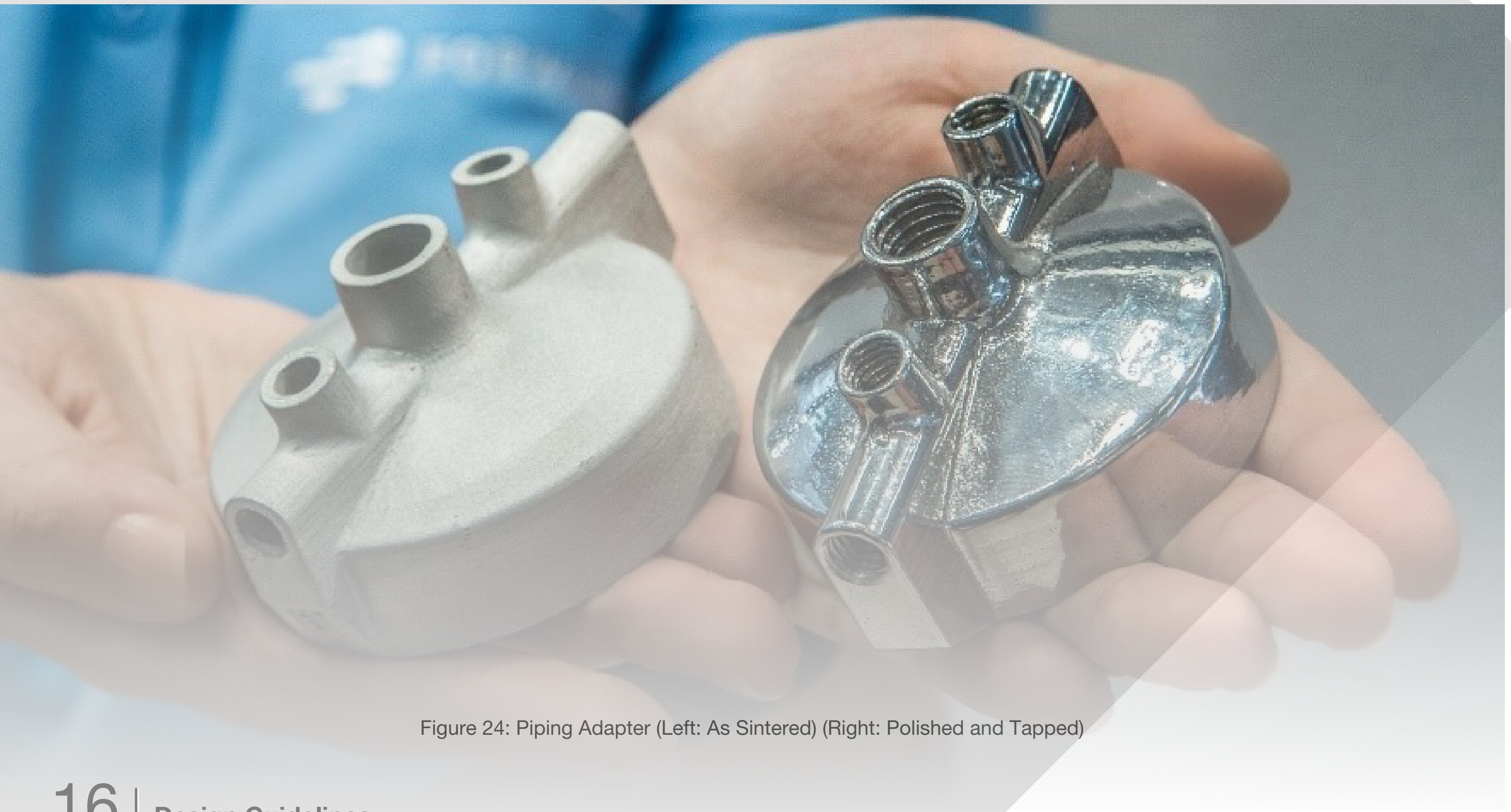


Figure 24: Piping Adapter (Left: As Sintered) (Right: Polished and Tapped)

Simulation Options

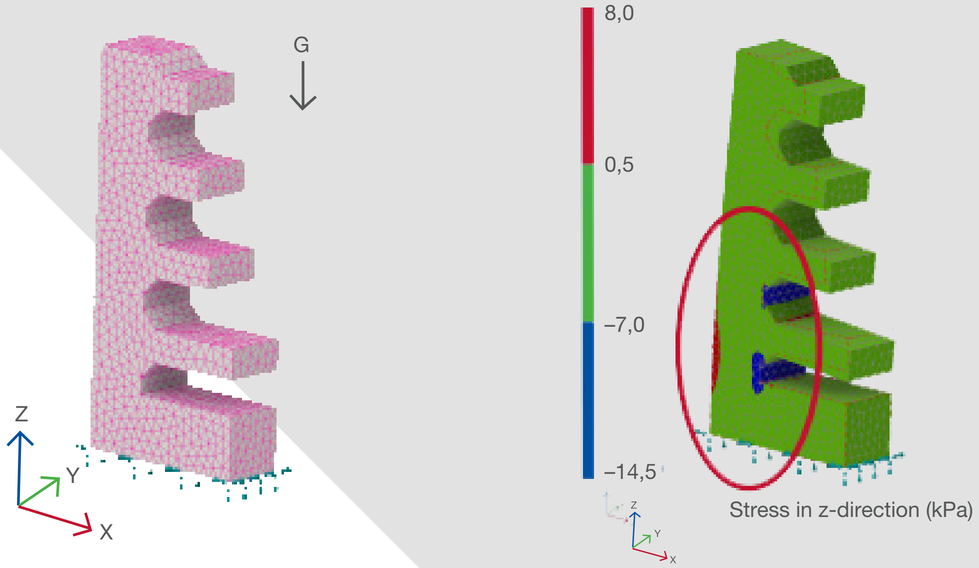
6

Simulation for additive manufacturing is a valuable step in the production of 3D printed parts. Engineers and 3D printing specialists work closely with designers to fully understand the perfect part orientation and support structure design, in order to reduce the number of iterations and tests during construction.
Through our part and process simulation service, we help our customers save time and costs: We identify and eliminate weaknesses ahead of production, thus reducing the risk of part failure. Our experts identify areas vulnerable to warping, delamination, and excessive deformation by leveraging a diverse set of detailed material models.
We offer 3 types of simulation options. If you would like to have more information and an offer, please get in contact to us at sales@basf-3dps.com.

- Debinding simulation
- Part orientation
- Shrinkage and Sintering Distortion

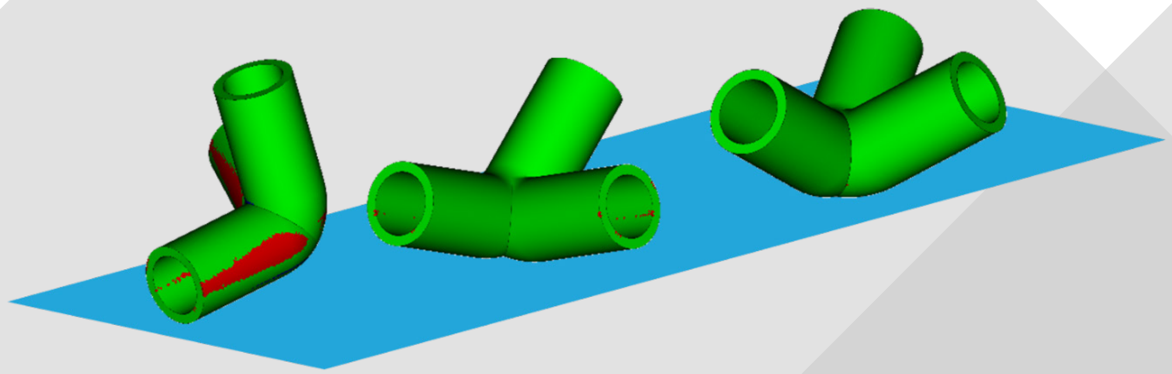
6.1 Debinding Simulation

Improper design or printing orientation have proven to be significant factors in part collapse during debinding. Internal tensile and compression stresses, resulting from gravitational forces, must be considered when choosing the appropriate design and orientation of Ultrafuse metal parts.
If you would like to conduct your own debinding simulation, a full procedure is available to guide users through the setup. The results of this tool can greatly increase the success rate of new metal filament users or those advanced users wishing to push their projects to the limits of lightweight structures, minimized print times, and final part performance.

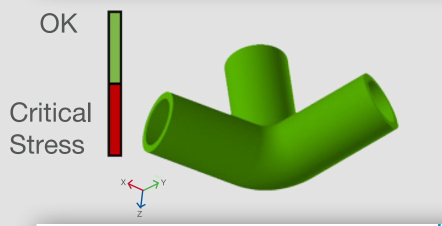
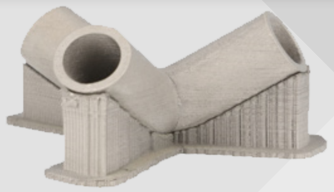


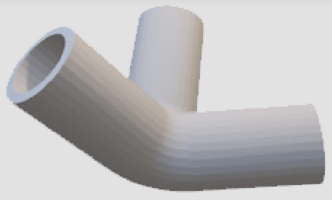
https://forward-am.com/wp-content/uploads/Debinding-and-Simulation-Guidelines.pdf

6.2 Part Orientation

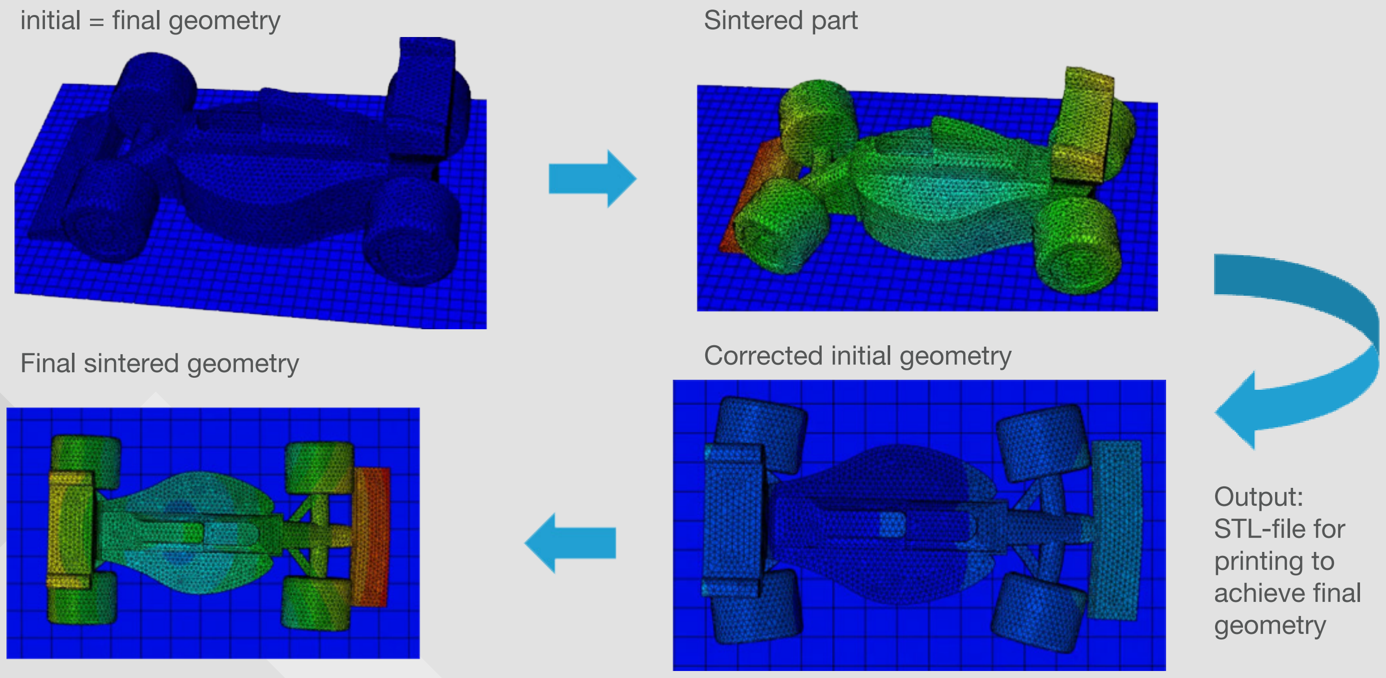


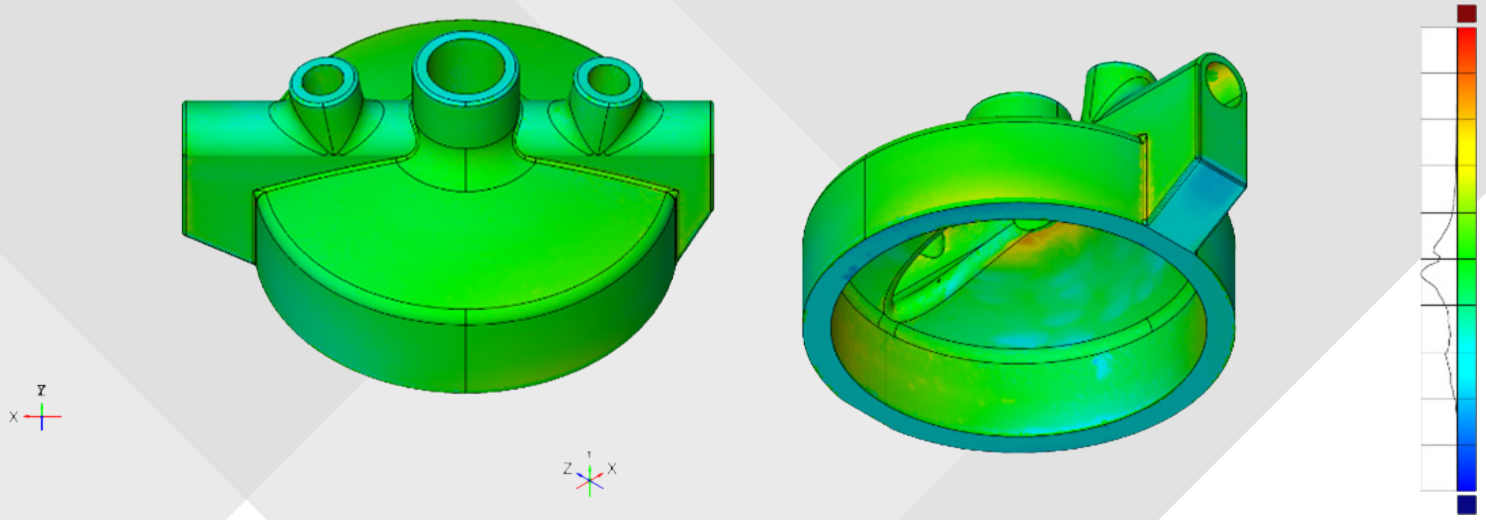
If a part's design cannot be changed, orientation optimization can help find an optimal part orientation best suited for debinding and sintering survival. This simulation provides a part orientation with minimal internal stresses and consequently the highest survivability. Please get in contact to us if you would like to take a

Simulation	3D-Printing	D&S
		
Several hundred alignments are tested to find the minimal internal stress	Optimal alignment with support structure	Reduction of iteration steps vie simulation

CAD Design	Printed Part	Sintered Result
		
For complex parts there be no obvious orientation for MF³	Usually it's sufficient to align parts according to experience	However, this can lead to iterative repetitions with complex parts

6.3 Shrinkage & Sintering Distortion





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