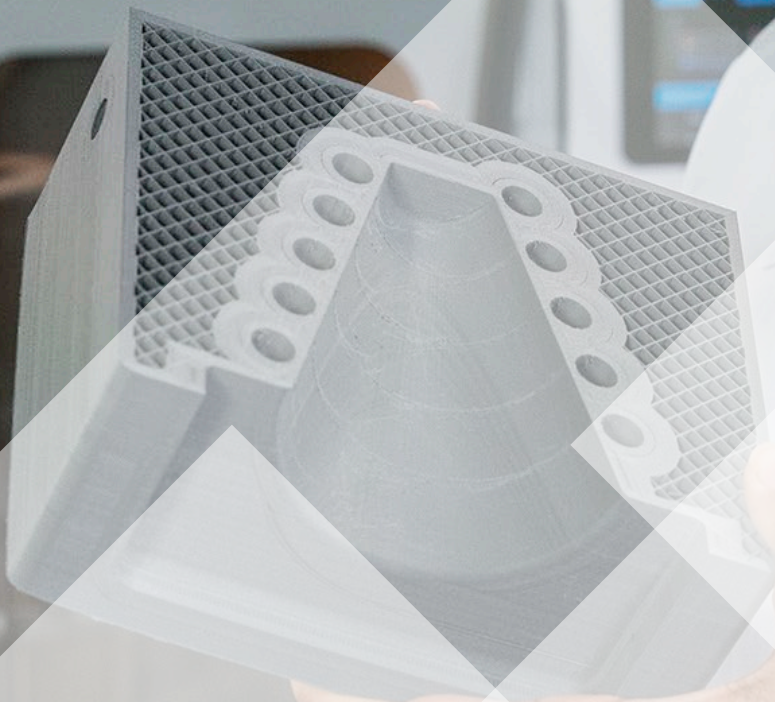




■ BASF
We create chemistry

Ultrafuse 316L

User Guidelines for
3D Printing Metal Parts



*“A great part starts
with great design”*



Ultrafuse 316L Video Tutorial

www.basf-3dps.com

Introduction

Ultrafuse 316L is a metal polymer composite filament especially designed for Fused Filament Fabrication (FFF). Once formed via 3D printing, parts undergo a debinding and sintering process. The catalytic debinding and sintering processes have been developed over the 25 years in which BASF has been active in Powder Injection Molding.

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Unlike Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Direct Metal Deposition (DMD) and Binder Jetting, enclosed internal features are made possible by the FFF nature of Ultrafuse 316L. In addition to this increase in capabilities, open format FFF printers are orders of magnitude less expensive than other metal component manufacturing hardware.

Production Process at a Glance

Ultrafuse 316L



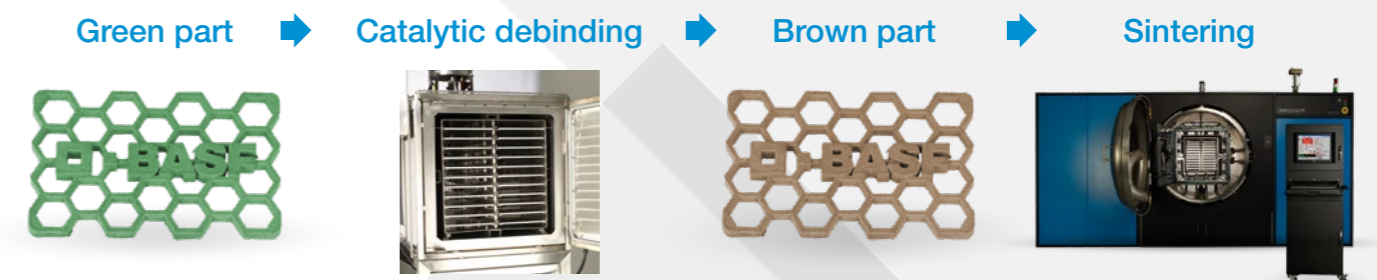
Slicing



3D Printing



Safe and professional solution for debinding and sintering



Metal part



1



Material

Ultrafuse 316L enables the printing of green parts without the need for a mold or other forming processes and has been specifically designed for open FFF 3D printers.

The high 90 percent metal content and the even distribution of the metal within the binder matrix reduces the risk of defects and increases the success rate. Due to immobilization of metal particles in the binder matrix into a filament dramatically reduces the potential hazards of handling fine metal powders when compared to Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Direct Metal Deposition (DMD) and Binder Jetting.

Ultrafuse 316L is compatible with both Bowden and direct drive extruders via the use of a non-slip outer surface. Possessing high flexibility, the filament can be guided through complex idler pulleys and guide roller filament transportation systems.

Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), & Slicing- “Art to Part”

Like any manufacturing process, FFF is subject to process-related constraints. 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 that is higher than that typically achieved with FFF.

To avoid frequent changes and a “trial and error” process, recommended design parameters are provided.

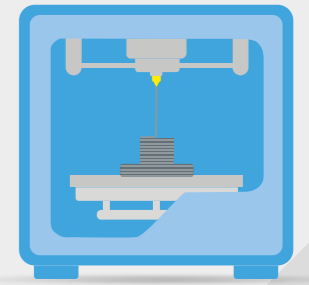
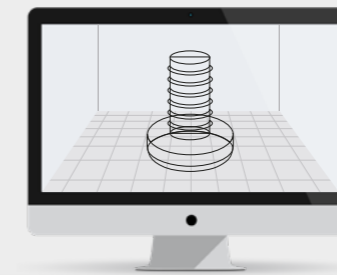


Slicing

Modeling Software

Each print starts with a computer generated model (examples for modeling softwares are CATIA, Autodesk Inventor, SolidWorks, Siemens NX, etc.). Regardless of the modeling software used, the outcome must be readable by the print preparation software “slicers.” Typical model formats include .stl, .obj, etc., which use triangles to describe the geometry. Selecting the size and variation of these triangles considerably impacts the resulting part tolerances. The slicer then converts the triangulated mode into machine code (G Code) by “cutting” the model into slices.

2



Printing Parameter	Value	Comment
Nozzle size	0.40 mm	Influenced by quality (details) and print time
Extrusion multiplier	1.0–1.1	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	45 mm/s	Recommended
Layer height	0.15 mm	Range of 0.10–0.25 mm (Resolution)
Outlines	1–2	Dependent of the part and print quality; overlap between the outlines must be provided
Infill %	100 %	Less than 100 % for hollow parts
Infill type	100 % (red.) <100 % Grid Honey comb	Min. 60 %
Outline overlap %	20–35 %	Should be checked; dependent on the printer
Infill extrusion width	100 %	100% recommended
Nozzle temperature	230 °C–250 °C	Actual temperature
Bed temperature	90 °C–120 °C	Actual temperature
Cooling	No cooling	Part cooling increases warpage
Default print speed	35 mm/s	Printing speeds depend on part complexity and size
Shrinkage	16 % XY 20 % Z	Regarding the scaling factor, see Shrinkage on page 12.

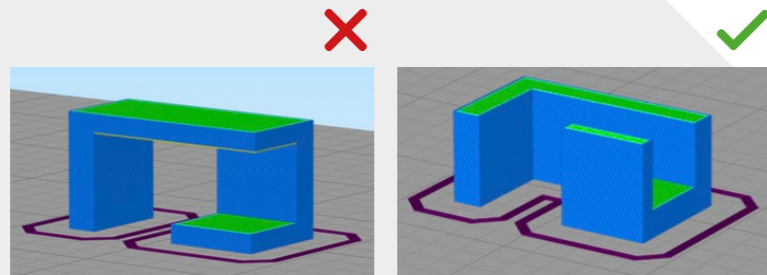
There are many parameters that can be changed, and some of them are critical for the quality of the print.

2



Part Orientation: Alignment of the Part Inside the Build Volume

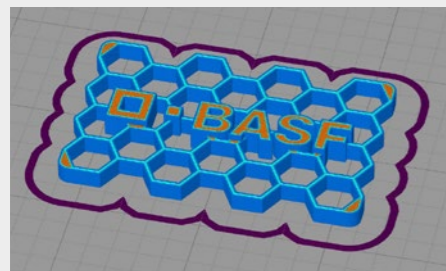
Parts should be orientated to minimize the need for supports.



Not good, support needed.

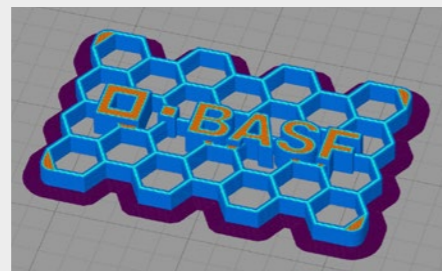
Good, no support needed.

Build Plate Adhesion/Additions



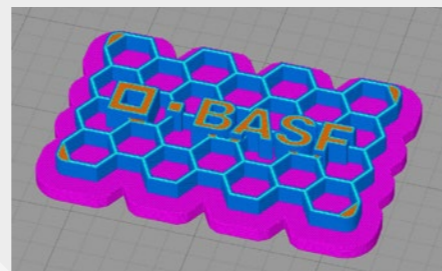
Skirt

Mainly used to prime the nozzle and to readjust the bed leveling during the print, if no brim or raft is used.



Brim

By experiencing corner warping or similar horizontal expansion of the surface.



Raft

Creates a bottom surface that the print can adhere to. This is a common solution to adhesion problems.

The Need of Support

As the sintering process begins, its metallic portions will slowly begin to coalesce, providing structural strength.

It is recommended to use a support when exceeding a 45° overhang angle. The same material is used as the support (the support infill structure should be dense, approx. 70 %) and can be removed in the green part state (the debinding and sintering strategy should be considered before removing the support material from the green part) or after sintering, again depending on the part geometry and complexity. A debound but unsintered part has the same structural integrity.

Many slicers work from the outer surface in. Therefore, when the extrusion width and wall thickness do not match, inner portions can be left either with no infill or partial infill.

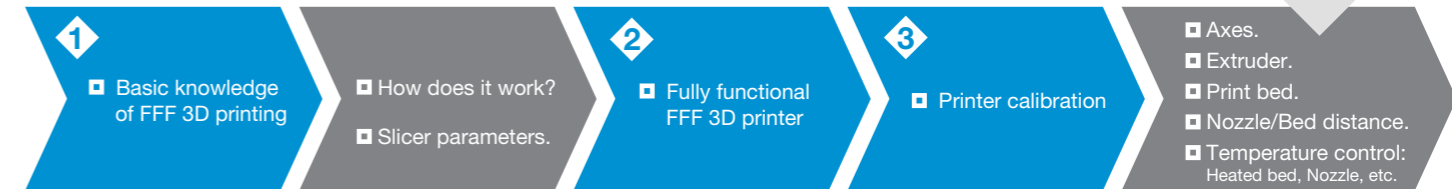
Fundamentals of Printing

Starting Requirements & Parameters

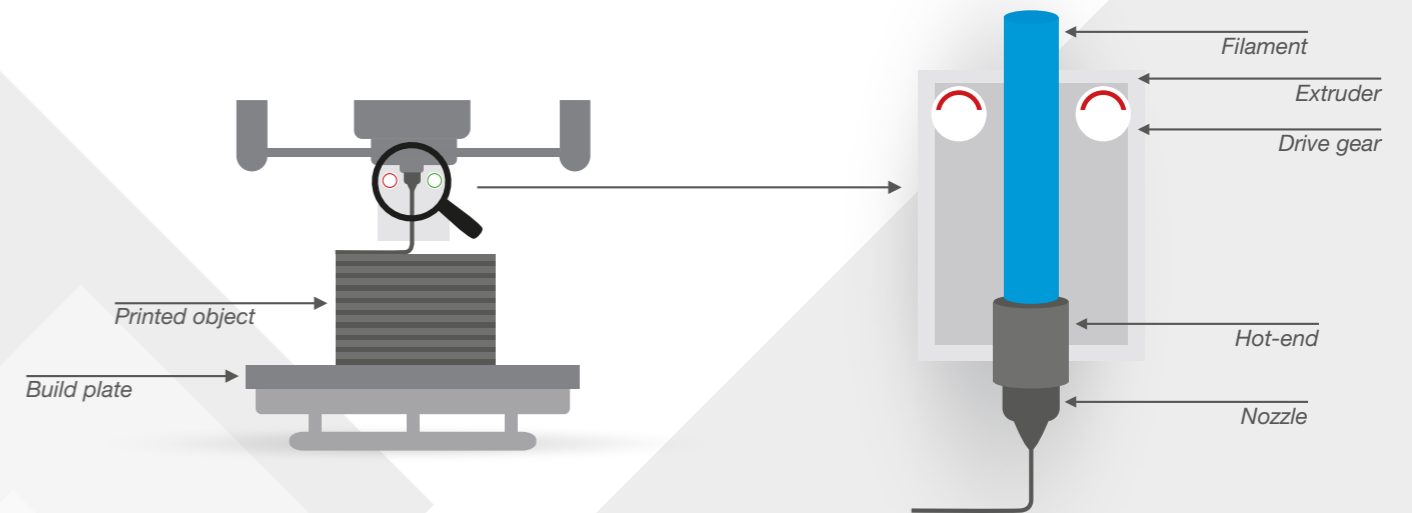
For successful printing, the following points are fundamental.



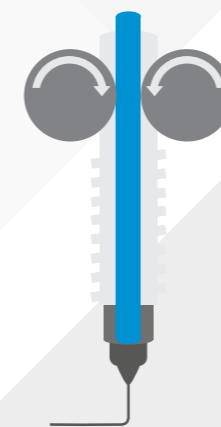
3



As with any FFF printing material, segments of Ultrafuse 316L are deposited on the printer's heated bed to form a layer. As successive layers of material are deposited, a 3D part is created, which is referred to as a green part. After printing, the part is then moved on to debinding and sintering (D&S).



Direct drive



Bowden drive



In metal FFF printing MF³, the metal composite filament is used as the material base. Printing with a metal filament is the same as printing with a plastic filament. However, there are subsequent process steps. After the component has been printed ("green part"), it must be debound, whereby the main binder is removed catalytically. The component after debinding is called the "brown part", it has a lower strength than the green part, but it remains dimensionally stable. During the sintering process, the brown part loses its second binder, and the individual metal particles fuse together.

Printer Requirements

Basically, it is possible to print the metal filament with a standard desktop FFF printer, but the machine influences the print quality and experience. Due to high warpage of the material, it is recommended to have an enclosed printing chamber with a low chamber air flow.

Minimum printer requirements	Recommended printer requirements
<ul style="list-style-type: none"> • Nozzle temperature up to 250 °C • Bed temperature up to 90–100 °C • Enclosed chamber • Low chamber air flow 	<ul style="list-style-type: none"> • Nozzle temperature up to 280 °C • Bed temperature up to 130 °C • Enclosed and heated chamber • Dual print head

Printing green part

Calibration and Benchmark Test

Introduction & first print tests with the Ultrafuse 316L metal filament

1. Single wall cube

- To define the correct extrusion multiplier
- Each material has different melting points and viscosities. This affects the extrusion multiplier and the extruded value during printing.

2. Process window

- The process window is an indicator of the printing speed as a function of the printing temperature.

3. Retraction test & part and end points

- To avoid strings between part features or parts

4. Printing accuracy test (can also be used for evaluation of the shrinkage value)

- Accuracy of the printer.
- Check if the printer is printing the correct dimensions.

5. Benchmark test

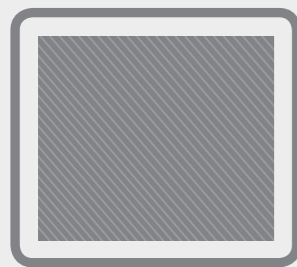
- Checking the printing parameters on a more complex part with different geometries.

First Layer

For successful printing, it is important that the first layer is printed satisfactorily. The first layer fixes the component during printing on the build plate.

Key points:

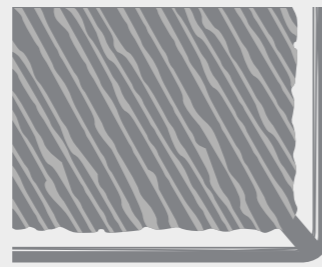
- ▣ Everything should be leveled and closed during printing.
- ▣ First layer should be adhered to the print bed.



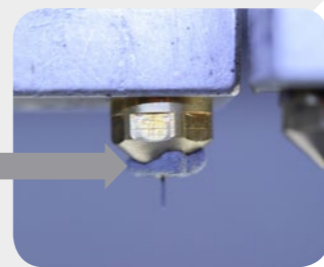
Even and closed. No swelling, not too "loose".



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.



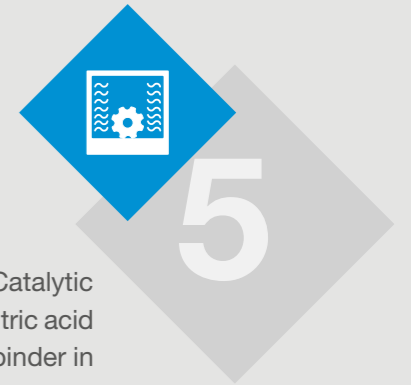
By smearing the extrudate that collects at the nozzle, this can lead to closure of the nozzle. Occasionally, the extrudate collects at the nozzle, which can lead to nozzle blockage.

Debinding brown part

Ultrafuse 316L uses multiple binder systems to ensure rapid and controlled removal of the primary binding material. Once the polymer-based binder has been removed, the part is referred to a brown part and is ready to be solidified into a fully metallic part by sintering.

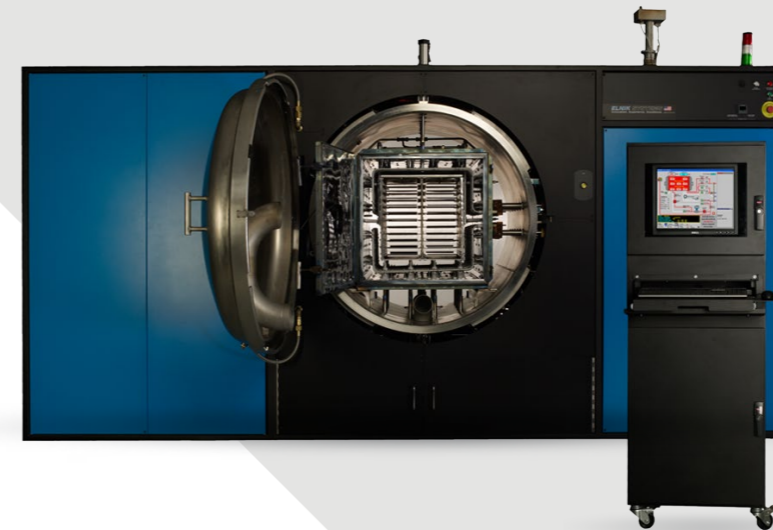
Debinding is the removal of binders which are required to enable the printing process. Catalytic debinding is a thermochemical process in which green parts are exposed to gaseous nitric acid (HNO₃) in a nitrogen atmosphere and heated. The goal of debinding is to remove the binder in the shortest amount of time with the least impact on the final part.

Additionally, economic considerations often limit maximum debinding times whereas catalytic debinding removes the binder material at highest rates in industry (1–2 mm/h for each external surface). In addition to the amount of time for the binding materials, a flushing cycle is required to remove residual HNO₃ or other decomposition by products.



Sintering white part

Brown parts are relatively porous and require sintering to produce a solid densified material. Sintering consolidates and forms a solid mass of material upon heat without melting the material, thus maintaining the part's shape.



Sintering in a pure hydrogen atmosphere enables the production of a finished stainless steel component that is almost fully dense. As a rule, the printing direction and parameters have a greater influence on shrinkage magnitudes than does part orientation in the D&S process. Support structures, as with any FFF part, are required when printing overhangs or other horizontal structures. Unlike typical FFF, however, Ultrafuse 316L requires increased support structures to ensure structural integrity throughout the D&S 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.





Post-Processing

Sintering produces pure metal parts that are ready for use. Tolerances of the surface quality may require further post-processing methods, such as polishing, milling, heat treating, and coating.



Before polishing



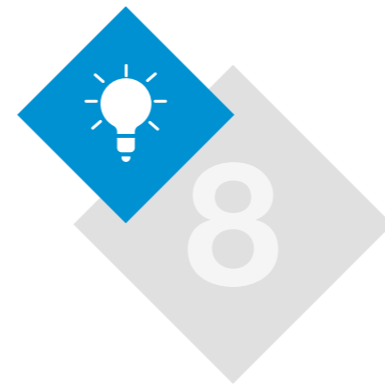
After polishing

Parts requiring high tolerances may take advantage of traditional metal working methods to produce functional faces. Green state machining enables dramatic reductions in machining costs and capital investment due to Ultrafuse 316L's high machinability in the green state.

The tool holder seen above was printed and sintered. After sintering, the supports were removed and higher tolerance features were finished, followed by tapping.



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.

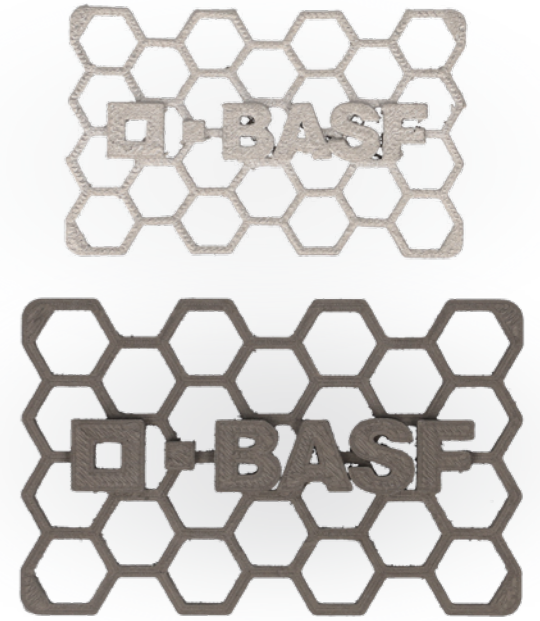


Guidelines

A great part starts with a great design. To enable the highest possible quality and performance, Ultrafuse 316L parts should be designed to exploit their advantages and avoid the limitations of both FFF and D&S.

Shrinkage

As individual metal particles coalesce into a solid mass, a reduction in the part size occurs, which is referred to as shrinkage. Anisotropic shrinkage occurs during the D&S process and is approximately 16 % in the X- and Y directions and 20 % in the Z direction. The figure on the right provides an example of typical part shrinkage from a green printed state to the fully sintered white part. Oversize factors are applied during the design stage to compensate for geometric changes and printing strategies. The following are general shrinkage guidelines under typical printing operations.



Even before the component design begins, process steps influence each other, such as the print direction, extrusion width, and layer height.



Shrinkage & Oversizing Factor

Equations & Examples

Catalytic debinding removes the primary binding materials of Ultrafuse 316L. 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.

$S \equiv$ Shrinkage (A measure of the reduction in size from green to sintered)

$OFS \equiv$ Oversizing factor (The amount to scale up a green part to produce the desired sintered part)

Typical Ultrafuse 316L shrinkage and oversizing factors:

$$S_x \approx S_y = 0.16 \text{ or } 16 \% \quad OFS_x \approx OFS_y = 1.20 \text{ or } 120 \%$$

$$S_z = 0.2 \text{ or } 20 \% \quad OFS_z = 1.26 \text{ or } 126 \%$$

How to convert between shrinkage and oversizing factors:

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

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:

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

$$L_{gxy} = 11.98 \text{ mm} \quad L_{gz} = 12.58 \text{ mm}$$

Result 1

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

$$X = 12 \text{ mm} \quad Y = 12 \text{ mm} \quad Z = 12.6 \text{ mm}$$

Example 2

Scale up the 10 mm cube in your slicer by:

$$X = 120 \%$$

$$Y = 120 \%$$

$$Z = 126 \%$$

Result 2

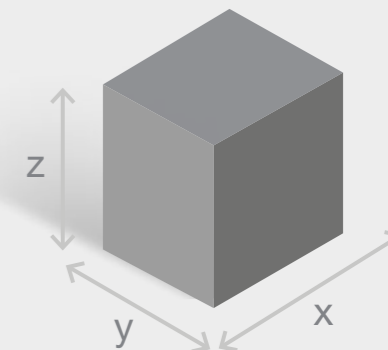
$$X = 12 \text{ mm}$$

$$Y = 12 \text{ mm}$$

$$Z = 12.6 \text{ mm}$$

Part Size

3D printing easily allows the production of >100 g parts. Part size is limited by the size of the print chamber, debinding, and the sintering oven size and brown part stability. Typical parts up to 100 mm have been most successful. Although achievable, larger parts can suffer from warpage from the build plate and often require longer development processes.

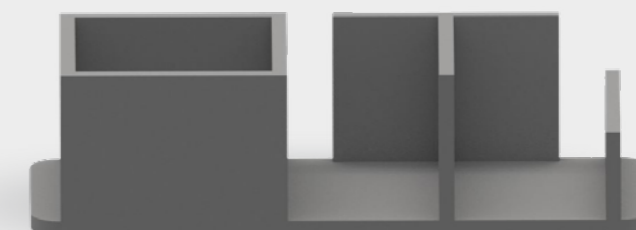


Feature Height

A debound but unsintered part has the lowest structural integrity. As the sintering process begins, its metallic portions slowly begin to coalesce, providing structural strength. To minimize the risk of structural collapse, height-to-width ratios of less than 3 to 1 are effective to prevent part collapse.

Wall Thickness

The wall thickness should be a multiple of the extrusion width, but not less than 1 mm. 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.



Wall Thickness & Slicing

The hexagonal sections have a wall thickness of 1.05 mm; with an extrusion width of 0.35 mm as shown on the left, three full extrusion widths created the wall structure whereas with an extrusion width of 0.40 mm, the slicer is forced to fill the gap with partial movements resulting in a decreased density.

The selection of an appropriate extrusion width (EW) must be calibrated prior to printing because it may dramatically affect the material infill and thus the mechanical properties and survival of the thin walls.

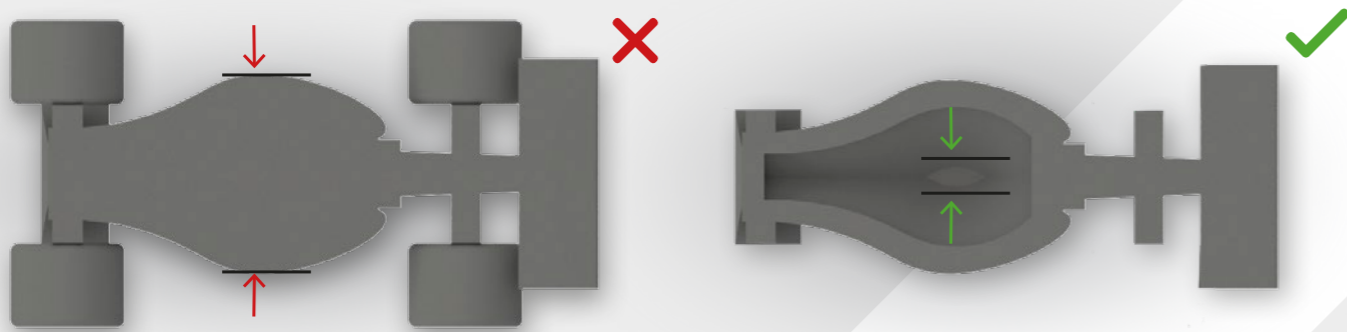


Example of a logopart.

Guidelines

Thickness and Debinding

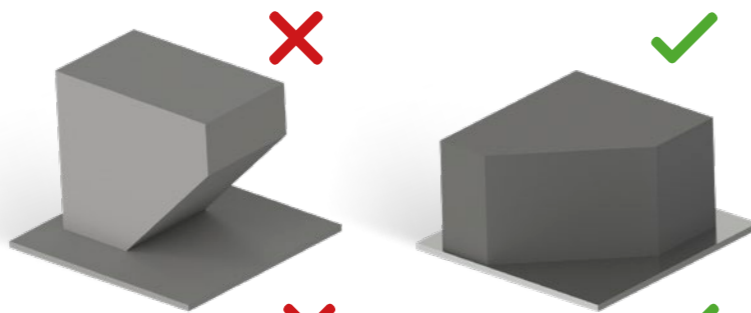
The thickest section of a part defines the total debinding time. Additionally, thin walls will debind faster; printing parameters such as the nozzle diameter, and EW may lead to the collapse of the thin walls during debinding. As the debinding process progresses, thinner sections may experience full removal of the binder, while thicker sections will require longer process times to fully remove the binder.



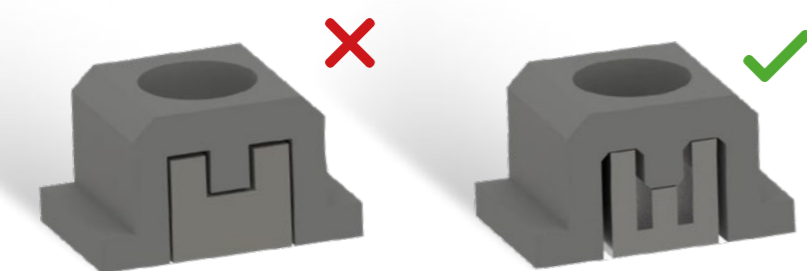
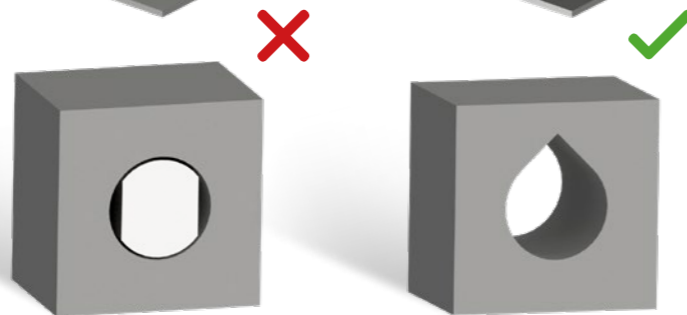
Supports

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. The figure on the right provides an example of a full overhang feature and its corresponding support.



If horizontal holes cannot be avoided, they should be altered as shown on the right to minimize ridging and/or the need for removal after sintering.



Simplify Support Removal

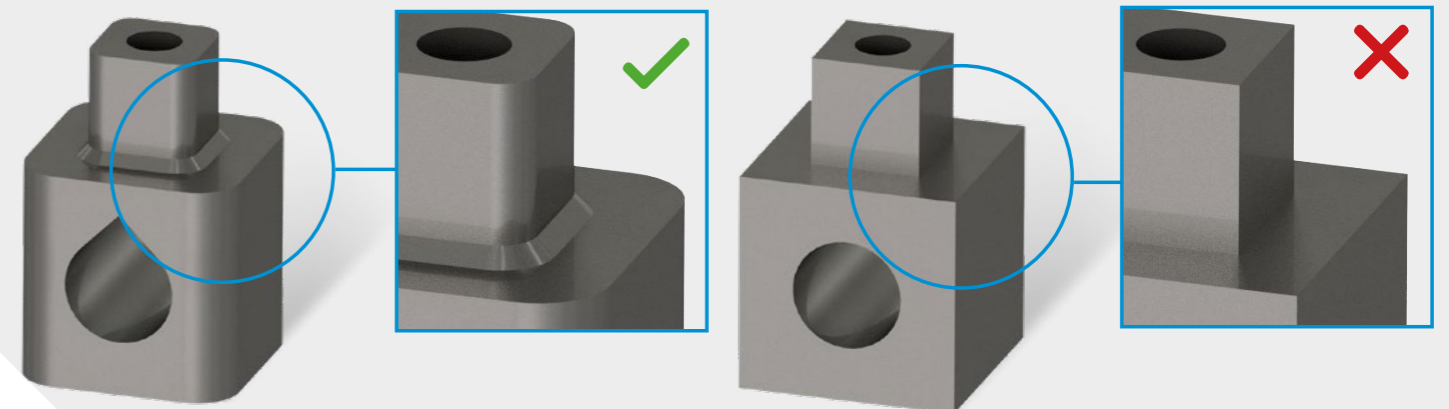
To minimize the need for post-processing, divide the support structure into individual segments by chamfering for manual removal during slicing.

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 circularity.

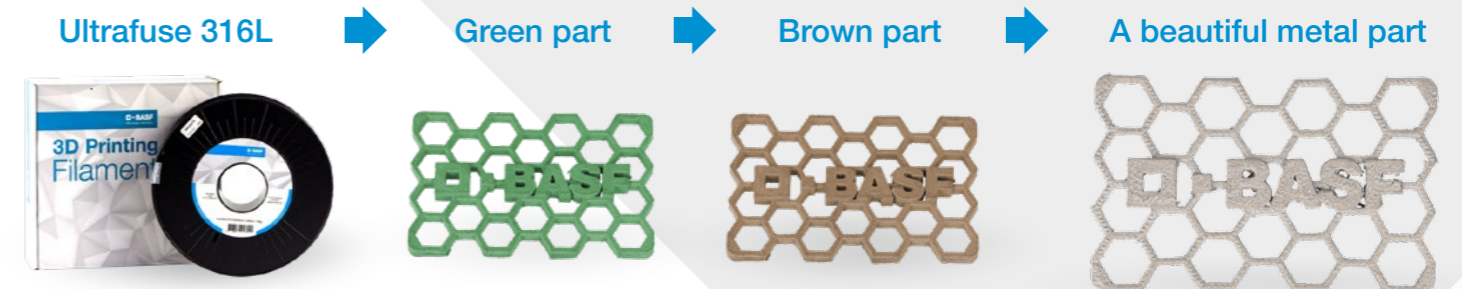


Transition

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 have been shown to reduce part cracking and increase part fidelity. If part geometry constraints limit redesign, the print orientation can often be adapted to reduce geometric distortion.



Are you ready? What's your next project?



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Service and Support



Product Development



Training



Debinding & Sintering



Design and Simulation Service

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