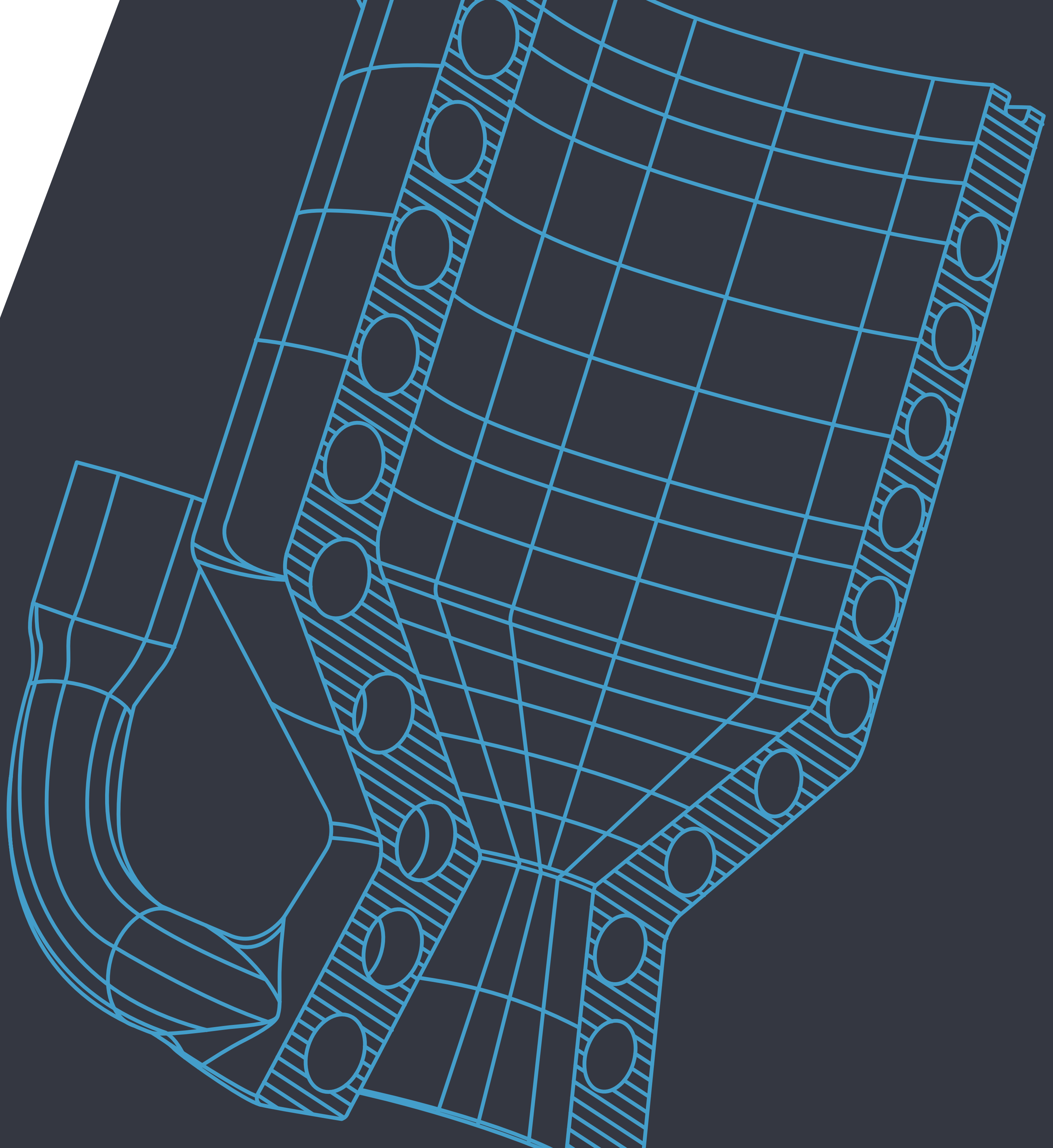
Designing for Metal 3D Printing

How to Leverage Additive Manufacturing for Metal Parts, Design for the Technology, and Use Post-process Finishing to Enhance Part Quality



PROTOLABS®
Manufacturing. Accelerated.®

Additive manufacturing for metal prototypes and production parts is enabling design solutions to the world's most complex and challenging engineering problems. The ability to create end-use, complex parts is delivering value everywhere from satellite launch systems to medical instrumentation to manufacturing tooling.

While not a substitute for traditional metal manufacturing, direct metal laser sintering (DMLS) can be used to produce part designs that would be otherwise unachievable. Common design goals for metal 3D-printed parts include:

- Manufacturability of complex geometries
- Lightweighting
- Part Consolidation
- Mass Customization
- Topology optimization
- Cost reduction

But 3D printing a quality metal part isn't as simple as designing a CAD file and hitting the print button. Quality 3D-printed parts are a result of understanding how to design for the process, using controlled and certified additive materials, printing with consistent and validated machine parameters, and utilizing state of the art post processing technologies.

Process Flow Chart

1 Design

A thorough review of the design is conducted. Part orientation and support structure is determined.

2 Build

The material is loaded into the machine and the build begins. Starting with the first support structures, the metal powder is sintered one layer at a time.

3 Stress Relief

While still attached to the build plate, parts are placed inside a furnace. Certain materials receive additional heat treatment to enhance material properties and/or satisfy customer requirements.

4 Support Removal

Parts are removed from the build plate with wire EDM or a band saw. Support structures are then removed from each part.

5 Finishing

Parts are media blasted as a standard process. If tighter tolerances or improved surface finish are needed, in-house custom machining/polishing operations are available.

6 Outsourced Operations

Application specific outsourced operations are available by request.

7 Inspection

Spot check measurements are completed on all parts. A full dimensional inspection and report are available by request from our in-house quality lab.

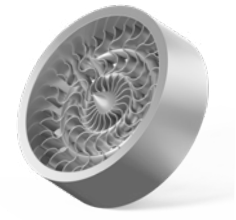
8 Shipment

Individual geometries are bagged by part number and shipped to customer.

Choosing the Right Metal for Additive Manufacturing

The metal powder used in DMLS is typically produced through an atomization process, which transforms raw metal material into 10 to 45 micron-sized spherical particles. The spherical morphology is critical to achieving uniform melted layers during the build, resulting in reduced risk of porosity developing within the part.

Stainless Steel
17-4 PH & 316L



Cobalt Chrome
Co28Cr6Mo

Aluminum
AlSi10Mg

Inconel
718

Titanium
Ti6Al4V

Copper
CuNi2SiCr

What Material Attributes Do You Need?

Strength

- Stainless Steels 17-4 PH and 316L
- Inconel 718
- Titanium (Ti6Al4V)
- Cobalt Chrome (Co28Cr6Mo)

Lightweight

- Aluminum (AlSi10Mg)
- Titanium (Ti6Al4V)

Temperature Resistance

- Inconel 718
- Titanium (Ti6Al4V)

Corrosion Resistance

- Stainless Steels 17-4 PH and 316L
- Inconel 718
- Titanium (Ti6Al4V)

Electrical/Thermal Conductivity

- Aluminum (AlSi10Mg)
- Copper (CuNi2SiCr)

Strength-to-Weight

- Aluminum (AlSi10Mg)

Material	Resolution	Condition	Ultimate Tensile Strength	Yield Stress	Elongation	Hardness
Stainless Steel (17-4 PH)	20 µm	Solution & Aged (H900)	199 ksi	178 ksi	10%	42 HRC
	30 µm	Solution & Aged (H900)	198 ksi	179 ksi	13%	42 HRC
Stainless Steel (316L)	20 µm	Stress Relieved	89 ksi	73 ksi	55%	94 HRB
	30 µm	Stress Relieved	92 ksi	72 ksi	58%	94 HRB
Aluminum (AlSi10Mg)	15 µm	Stress Relieved	45 ksi	31 ksi	8%	46 HRB
	30 µm	Stress Relieved	50 ksi	33 ksi	8%	59 HRB
Titanium (Ti6Al4V)	20 µm	Stress Relieved	153 ksi	138 ksi	15%	35 HRC
	30 µm	Stress Relieved	144 ksi	124 ksi	18%	33 HRC
Cobalt Chrome (Co28Cr6Mo)	20 µm	As Built	182 ksi	112 ksi	17%	39 HRC
	30 µm	As Built	176 ksi	119 ksi	14%	38 HRC
Inconel (718)	20 µm	Stress Relieved	143 ksi	98 ksi	36%	33 HRC
	30 µm	Stress Relieved	144 ksi	91 ksi	39%	30 HRC
	30 µm	Solution & Aged per AMS 5663	208 ksi	175 ksi	18%	46 HRC
	60 µm	Stress Relieved	139 ksi	83 ksi	40%	27 HRC
	60 µm	Solution & Aged per AMS 5663	201 ksi	174 ksi	19%	45 HRC
Copper (CuNi2SiCr)	20 µm	Precipitation Hardened	72 ksi	63 ksi	23%	87 HRB

These figures are approximate and dependent on a number of factors, including but not limited to, machine and process parameters. The information provided is therefore not binding and not deemed to be certified. When performance is critical, also consider independent lab testing of additive materials or final parts.

Before the Build

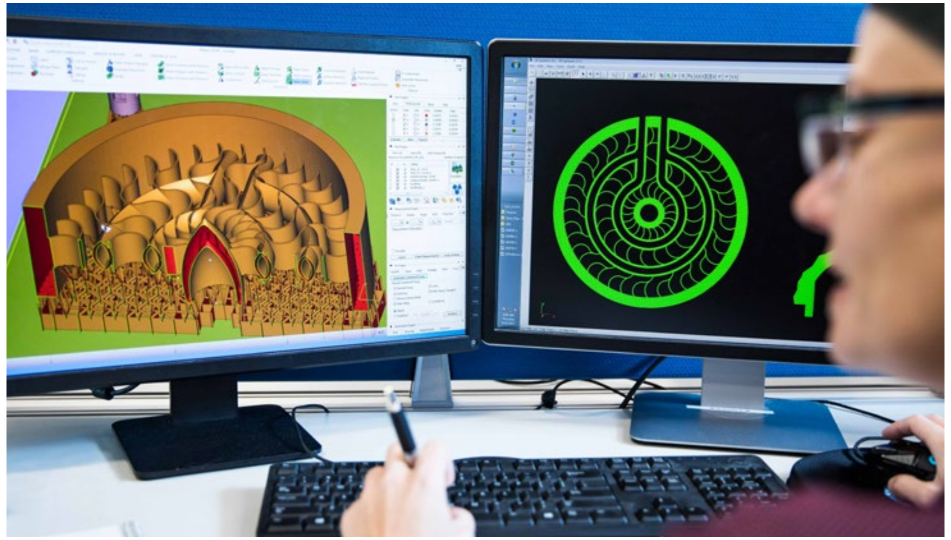
Design Considerations to Improve Metal Parts

Let's take a look at some basic guidelines on how to design features on metal 3D-printed parts. Keep in mind that parts can be built in normal (30 or 60 micron) or high (15 or 20 micron) resolution. The two main factors to consider when selecting a resolution will be the part's overall size and minimum feature sizes. Here are the part parameters at Protolabs:

Maximum Dimensions	Normal Resolution	9.6 in. x 9.6 in. x 13.0 in. (245mm x 245mm x 330mm)
	Normal Resolution (Inconel 718 or Aluminum built on X Line 2000R)	31.5 in. x 15.7 in. x 19.7 in. (400mm x 800mm x 500mm)
	High Resolution	3.5 in. x 3.5 in. x 2.7 in. (88mm x 88mm x 70mm)
Layer Thickness	Normal Resolution	0.0012 in. (30 microns)
	Normal Resolution (Inconel 718 or Aluminum built on X Line 2000R)	0.00236 in. (60 microns)
	High Resolution	0.00079 in. (20 microns)
	High Resolution (Aluminum only)	0.0006 in. (15 microns)
Minimum Feature Size	Normal Resolution	0.015 in. (0.381mm)
	Normal Resolution (Aluminum only)	0.030 in. (0.762mm)
	Normal Resolution (Inconel 718 or Aluminum built on X Line 2000R)	0.015 in. (0.381mm)
	High Resolution	0.006 in. (0.153mm)

Designing for Cost Reduction

- Design parts that can be self-supported to minimize the need for support structures and their removal
- Reduce material usage through topology optimization, hollowed-out features, and leveraging mesh and/or lattice structures



Anatomy of a part

Wall Thickness

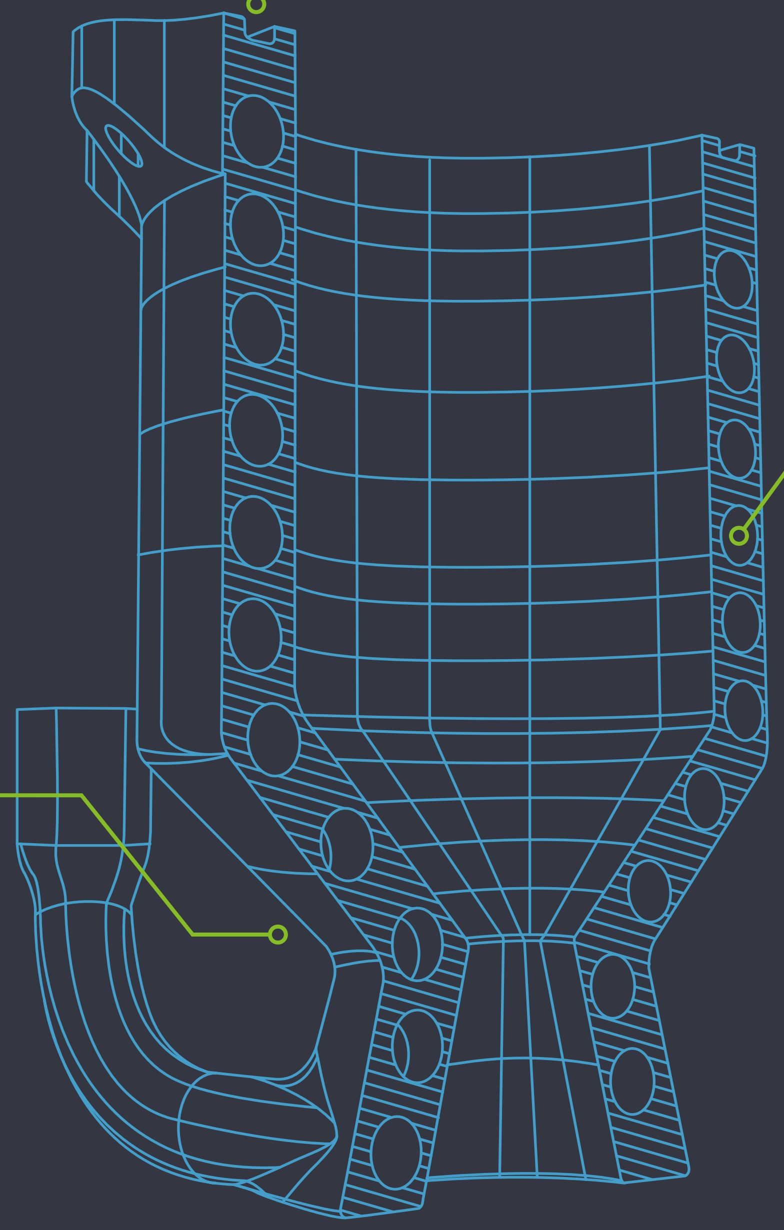
Depending on geometry, walls under 0.040 in. (1mm) have a high risk for build defects. Reinforcing thin walls with bracing, ribs, and gussets will reduce warpage during the build and maximize wall height.

Bridges

The minimum allowable unsupported distance we recommend is 0.080 in. (2mm). Exceeding this recommended limit will result in poor quality on the down-facing surfaces and the feature will not be structurally sound.

Self-Supporting Angles

Angle self-supported features no less than 45 degrees from the build plate. For 316L stainless steel, and Copper CuNi2SiCr the minimum self-supported angle is 55 degrees. As the angle of a self-supported feature decreases, the down-facing surface will become rougher and the risk of a build failing increases. Designing self-supported features will reduce costs by accelerating build speed and eliminating the need for support structure removal after the build.



Lattice Structures

Designing parts with lattice or mesh structures can reduce material and weight for a part. Maintain an angle greater than 45 degrees from the build plate and bridge distances no larger than 0.08 in. (2mm). Minimum strut diameter is 0.015 in (0.38mm) for normal resolution and 0.01 in. (0.25mm) for high resolution.

Channels

Channels can be any size if designed to be self-supporting such as a diamond or tear drop shape. If circular channels are required, maintaining a diameter no larger than 0.30 in. (8mm) is recommended to reduce roughness on down-facing surfaces.

Text

For best results, text should be inset at 0.015 in. (0.381mm) deep, 10-point font or larger, and bold if possible. Also consider the space between each digit—a minimum of 0.006 in. (0.1524mm) gap for high resolution and 0.012 in. (0.3048mm) for normal resolution is advisable.

During the Build

Creating Precision Parts Every Time

▶ Tolerances

For well-designed parts, tolerances of ±0.003 in. (0.076mm) plus ±0.001 in./in. (0.0254mm/mm) for each additional inch can typically be achieved. Note that tolerances may change depending on part geometry.

▶ Support Structures

Support structures are necessary to connect parts to the build plate, hold features in place, and prevent warping. They also act as heat sinks during the production process by transferring heat from the part to the build plate. Designs with thick cross sections will require more support structures to combat the stress that builds up within the part and prevent the part from pulling itself off the build plate.

▶ Part Orientation

When determining the optimal build orientation, there are several factors to consider: minimizing support structures, accessibility to support structures for removal, warpage, build time, and surface finish quality.

▶ Surface Roughness

Surface roughness will vary depending on the material, machine parameters, and part orientation. A typical metal 3D-printed part will have a surface finish of 200 to 400 µin Ra, which can be improved upon with machining or polishing after the build. The first, down-facing surface in a build will typically extend deeper than the nominal layer thickness, resulting in roughness.

In Pursuit of Precision

Machine Parameters

Dialing in the correct machine parameters is critical to achieving quality parts in a variety of materials. For example, the machine's laser power must be carefully calibrated in order to melt powder particles of each layer consistently, but too much energy will lead to defects and less dense parts. Other parameters on the machine include scan speed, spot size, and layer thickness.

Statistical Process Control (SPC)

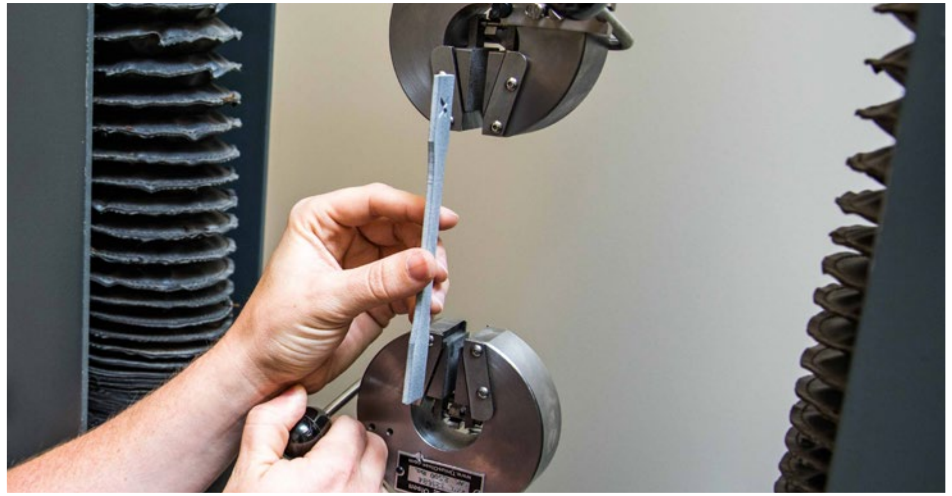
SPC parts are included on every build to identify any trends in part quality:

- SPC parts used to validate tensile strength and dimensional accuracy
- Mechanical properties tested per ASTM E8 standard
- Density coupons tested

How Material Handling and Power Analysis Improve Part Quality

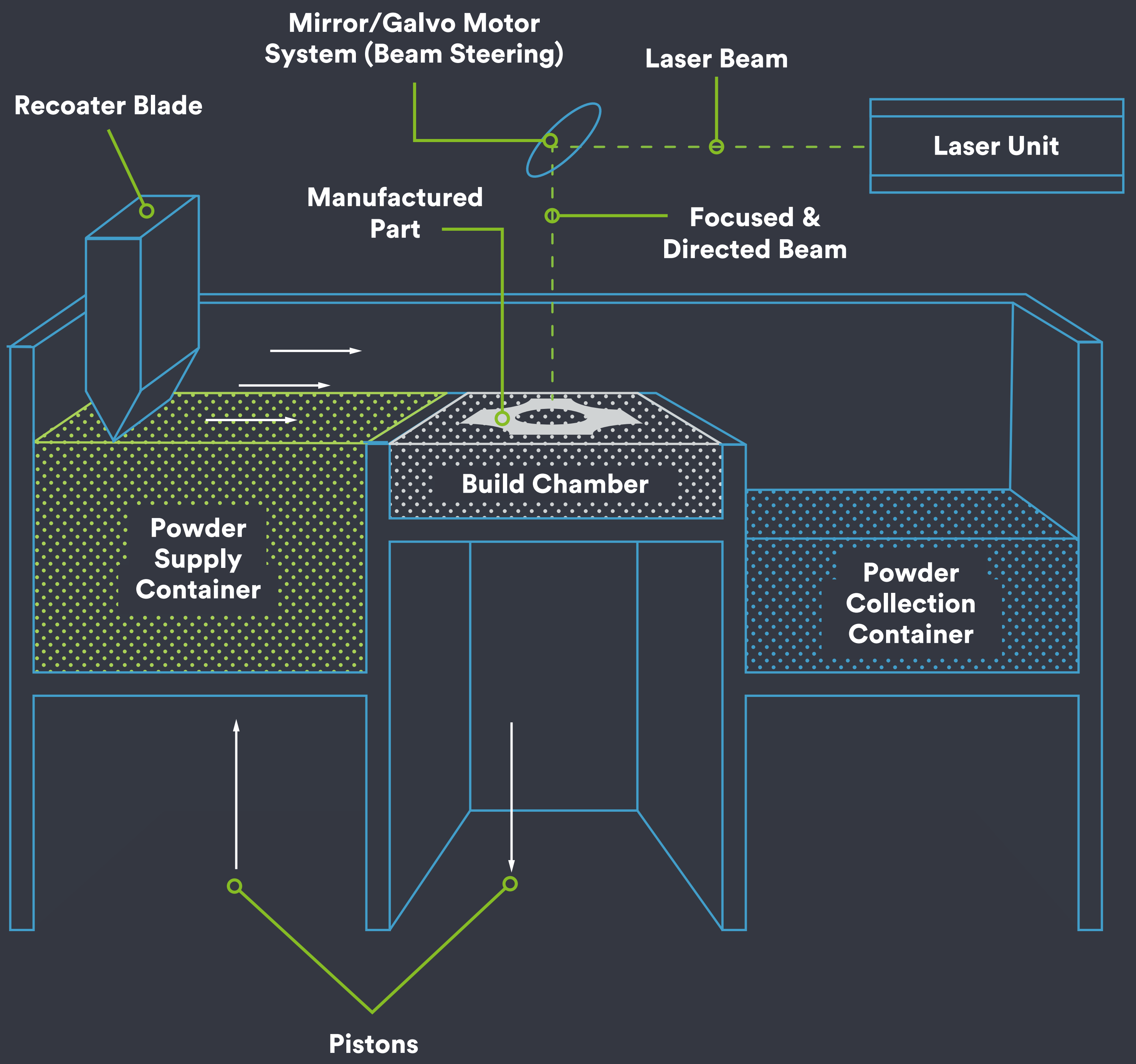
Protolabs takes the following steps to ensure materials meet quality requirements:

- Material is purchased per its ASTM standard
- Powder is tested to ensure material adheres to chemical composition defined by the respective ASTM document
- Regular testing for particle size distribution
- Powders used for each build can be traced back to supplier



Anatomy of a Machine

Once a thorough review of the part file is complete, part orientation and support structure placement are determined based on the application's requirements. The CAD model is then digitally sliced into layers and sent to the DMLS machine for production.



Beyond the Build

Post-Production Processing to Enhance Parts

With metal 3D printing technology, you're able to choose from several secondary processes like post-process machining, tapping, reaming, and heat treatments that produce end-use production parts. To ensure high-quality parts, we also offer process validation and inspection reporting, and our DMLS 3D printing process is ISO 9001-and AS9100D-certified.

Standard Secondary Processes

Standard Stress Relief: While still attached to the build plate, parts receive a standard heat treatment.

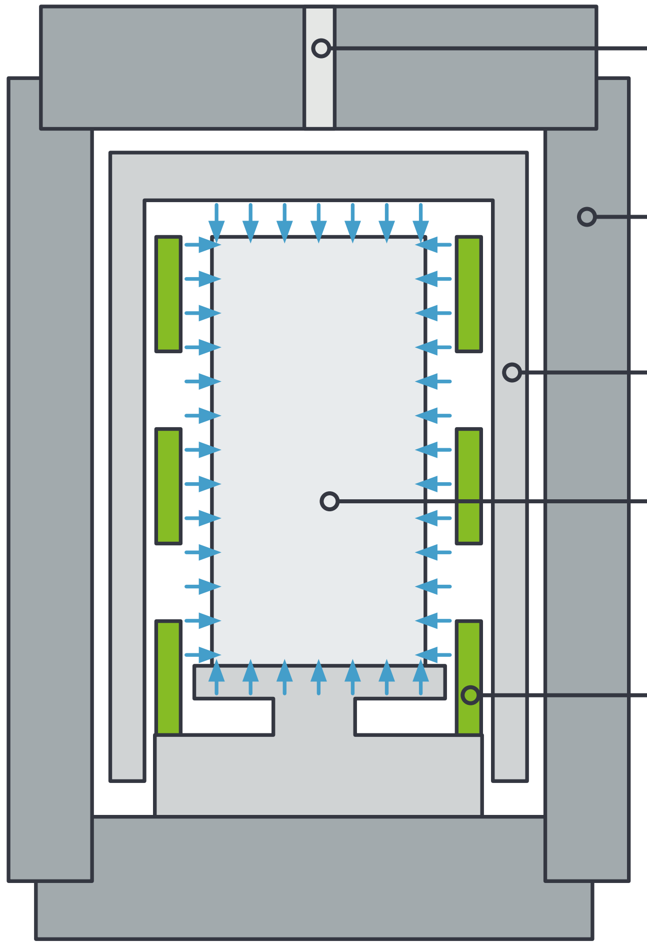
Support Structure Removal: After the build is complete, parts need to be removed from the build plate. Wire EDM is often used for this step. Support structures are removed in a variety of ways depending on part geometry and application requirements.

Additional Heat Treatments

Hot Isostatic Pressing (HIP): This process combines high pressure and temperature to eliminate any potential of porosity within the part and reduce anisotropy. It also increases resistance to impact, wear, and abrasion. Typically HIP is used for aerospace components that will be under heavy loads.

Solution Annealing: The heat treatment process heats the workpiece above its recrystallization temperature and cools it down to relieve stresses and change microstructure. This is most commonly used for stainless steel parts as it reduces hardness and increases ductility.

Aging: This is a secondary heat treatment process applied to certain metal alloys. Part temperature is elevated and held for a designated time to cause precipitate formation. Our standard process is to age 17-4 stainless steel to the H900 condition. By request, Inconel 718 may also be aged to boost temperature resistance, strength, and hardness properties.



Finishing

Once heat treatment is complete, parts will then be machined if required. With post-process machining, tighter tolerances and improved surface roughness can be achieved. This is especially useful for parts with mating features.

Machining (Milling, EDM): Post-build CNC machining can be used to achieve tighter tolerances on features called out in the drawing. Typically, tolerances of +/- 0.001 in. Keep in mind that parts that will be machined need to be fixtured within a machine so curved or beveled surfaces can create challenges. In some instances, a sacrificial portion can be designed into the part to aid in fixturing and be removed after the process.

Tapping and Reaming: Parts with holes or threading can be tapped and reamed for accuracy.

Polishing: Using hand tools, polishing can achieve a near mirror finish on parts. If a surface requires polishing, be mindful that it is accessible.

Inspections

A variety of methods can be used to validate the part's geometry is in accordance with the supplied drawing.

Coordinate-Measuring Machine (CMM)

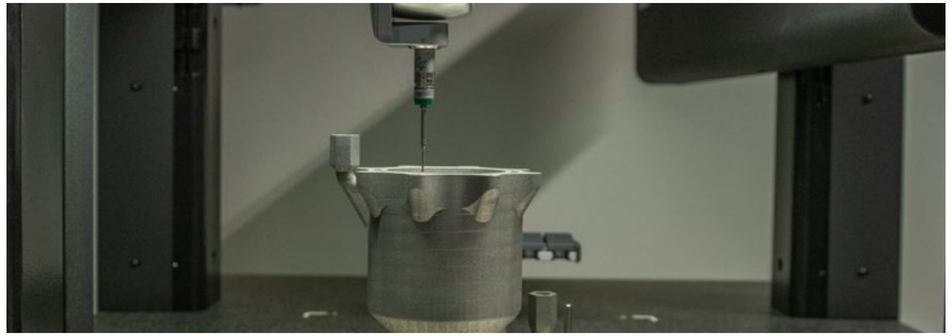
A CMM can be used to gather precision measurements to validate part features are within specified tolerances.

Computed Tomography (CT) Scanning

CT scanning provides a non-destructive means of validating internal features like channels and holes and ensures no unsintered powder or porosity is present within the part.

First Article Inspection (FAI)

First article inspection reporting in accordance with AS9102 is often used for parts that will be put in flight.



Get production-grade metal parts as large as 31.5 in. x 15.7 in. x 19.7 in. (800mm x 400mm x 500mm) 3D printed in highly durable Inconel 718 and lightweight Aluminum AlSi10Mg. Our large format GE Additive X Line machines produce metal 3DP components that are ideal for larger 3DP designs—or when combining multipart assemblies—and is well suited for various applications in aerospace, medical, industrial machinery, and other segments.

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