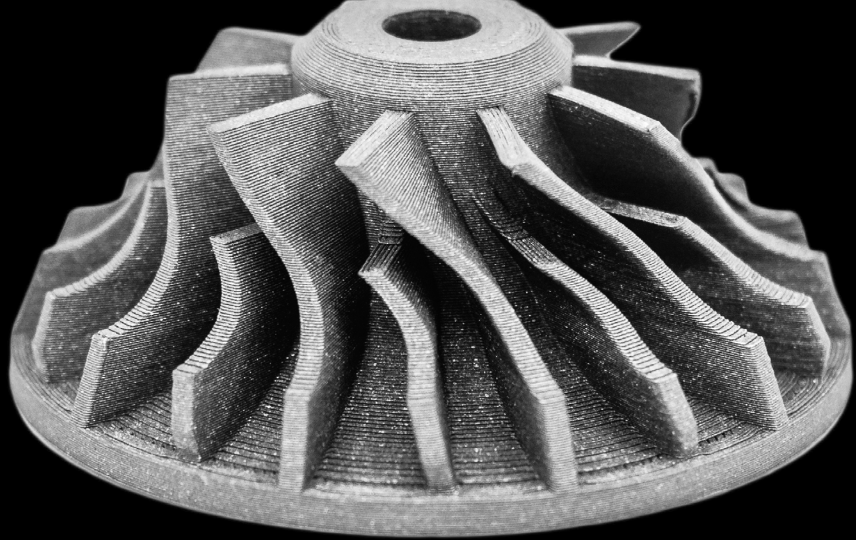
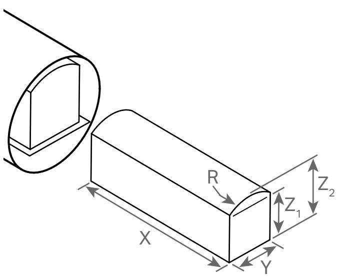
Markforged

Design Guide for 3D Printing with Metals



Metal X Design Reference Sheet

Listed dimensions are as designed for your final part unless otherwise specified. These guides serve as recommendations and may not reflect all implementations, since 3D printing is a geometry dependent process.

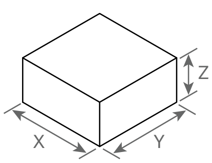


Maximum Final Part Size

These are the maximum post-sintered dimensions of a single part made with the Metal X system, including scaloing factors, print volume, part raft and setter tray.

	Sinter-2 Stacked Setter Configuration		Sinter-2 Single Setter Configuration	Sinter-1
	Upper Setter Plate Stacked	**Lower Setter Plate Stacked**	**Lower Setter Plate Alone**	**Setter Plate Standard**
X:	235.0 mm (9.25”)	235.0 mm (9.25”)	235.0 mm (9.25”)	235.0 mm (9.25”)
Y:	181.6 mm (7.15”)	75.0 mm (2.95”)	123.3 mm (4.85”)	68.3 mm (2.69”)
Z_2:	93.9 mm (3.70”)	56.0 mm (2.20”)	161.9 mm (6.37”)	80.9 mm (3.19”)
Z_1:	37.9 mm (1.49”)	N/A	141.3 mm (5.56”)	69.2 mm (2.72”)
R:	102.5 mm (4.04”)	N/A	102.5 mm (4.04”)	55.5 mm (2.19”)

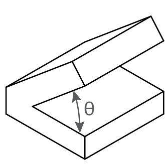
Use the Stacked Setter configuration for batches of parts and wide parts, and use the Single Setter Configuration for tall parts.



Minimum Part Dimensions

X: 2.0 mm (0.079”)
Y: 2.0 mm (0.079”)
Z: 1.3 mm (0.049”)

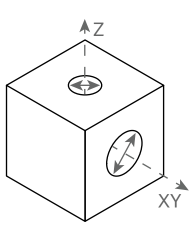
Minimum part size is limited to the extrusion width and height of each bead. The dimensions are derived from the minimum number of roof layers, floor layers, and shells needed to print a part successfully.



Unsupported Overhang

17-4 PH, A2, D2, H13	Inconel, Copper
θ: 45°	θ: 50°

This is the minimum angle to the horizontal at which a feature of a part can print without needing supports to hold it up. Eiger will generate supports for all overhangs with angles below θ.

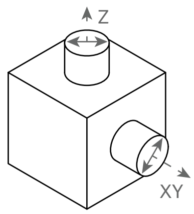


Minimum Hole Diameter

XY: 1.5 mm (0.059”)
Z: 1.0 mm (0.039”)

Holes with too small a diameter may close off during printing or print inaccurately. Horizontal surface holes (Z) print more precisely than vertical surface holes (XY).

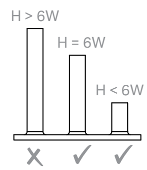
Metal X Design Reference Sheet



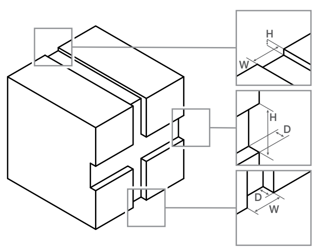
Minimum Post Diameter

XY: 3.0 mm (0.118")
Z: 3.0 mm (0.118")

Posts with too small a diameter may not print or sinter precisely. Consider adding fillets to the bases of posts to reduce the potential for shearing in the green state.



Important note: Avoid freestanding features with heights (H) more than six times their width (W). These are more susceptible to lean during sintering. Integrate inherently stable features like ribs or draft angles to support them.



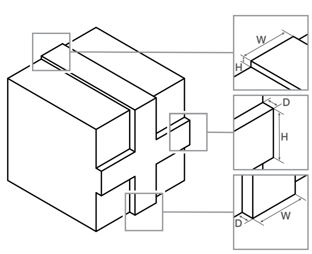
Minimum Engraved Features

Z Layer features
H: 0.13 mm (0.005")
W: 0.50 mm (0.019")

Horizontal XY features
H: 1.5 mm (0.059")
D: 0.5 mm (0.019")

Vertical XY features
W: 0.5 mm (0.019")
D: 0.5 mm (0.019")

An engraved feature is one that is recessed below the surface of the model. Common examples include lettering and texture. Engraved features may blend into the rest of the model if they are too small.



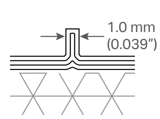
Minimum Embossed Features

Z Layer features
H: 0.13 mm (0.005")
W: 1.0 mm (0.059")

Horizontal XY features
H: 1.3 mm (0.049")
D: 0.5 mm (0.019")

Vertical XY features
W: 1.0 mm (0.059")
D: 0.5 mm (0.019")

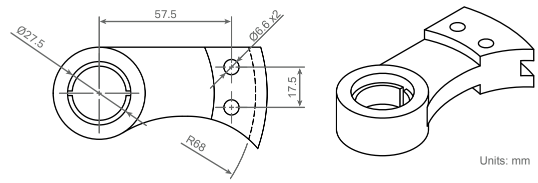
An embossed feature is one that is raised above the surface of the model. Common examples include lettering and texture. Embossed features may blend into the rest of the model if they are too small.



Important note: To eliminate gaps in features less than than 2.0 mm (0.079") wide, design embosses to be even multiples of 0.25 mm (0.01"), the width of a single post-sintered extrusion of metal.

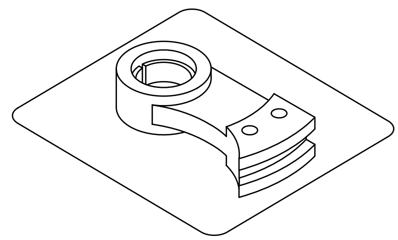
Optimize For Printing

As you design your part, consider how it can be optimized for the printing process. Below are four considerations to keep in mind when designing:



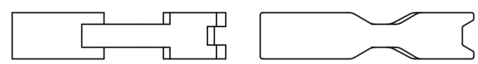
1. Identify Critical Dimensions

3D printers have higher precision in planes parallel to the build plate. What are your critical dimensions or features?



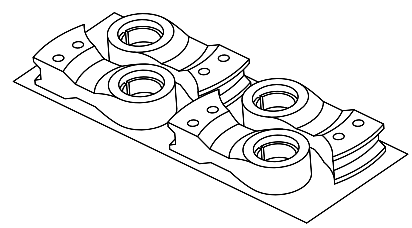
2. Maximize Bed Contact

Greater surface area on the print bed minimizes supports and improves bed adhesion. Which face of your part contacts the bed?



3. Reduce Supports

Fewer supports reduce printing and processing time. How can you design to minimize supports? Are the supports in your part accessible?



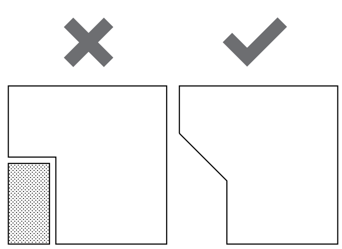
4. Optimize Your Production Workflow

Consider overall throughput. How will parts pack in the furnace to lower batch costs? Can your production schedule accommodate much longer print/wash/dry times for solid infill parts? When should you kick off print / sinter runs to optimize throughput?

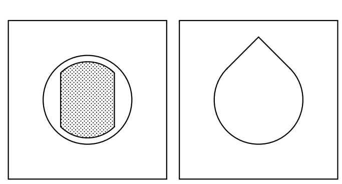
Modify Overhangs to Optimize Supports

Supports are necessary to prevent overhang collapse during printing and sintering. Consider where your parts will require supports and what you can do to minimize supports to decrease print time. Ensure the supports on your part are easy to remove before you print. If not, consider modifying overhangs to improve support removal, or use the Separable Supports Alpha Feature (See Alpha Support Structures Guide) to break up your supports and make each segment easy to extract.

Eliminate Supports

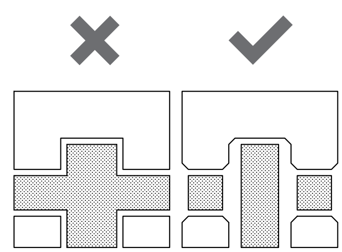


Chamfer small overhangs
Refer to Maximum Unsupported Overhang, pg 2

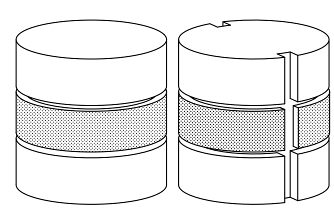


Teardrop XY holes to clear channels

Simplify Support Removal

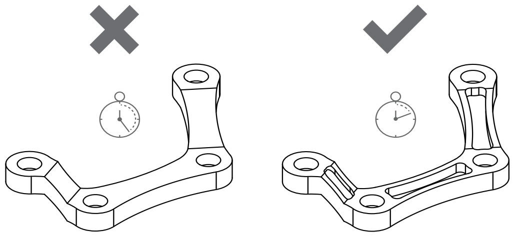


Break up supports with chamfers on edges
Refer to Maximum Unsupported Overhang, pg 2



Add slits to separate segments

Optimize For Washing

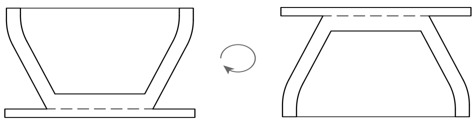


Thicker part sections increase wash time

Shell parts for a faster wash time

Shell Out Thick Parts

The thicker your part is, the longer it will take to wash. Shell out large volumes and increase surface area to minimize the time your parts spend in the wash. Try to maintain consistent wall thickness across your part.



Slower wash time in printed orientation

Faster wash time when inverted

Wash Bowls Upside Down

Wash bowl-shaped parts upside down (no need to change print orientation). The washing solvent is lighter than the binder material. When upside-down, the solvent permeates up into the bowl, resulting in a faster wash time.

Triangular vs. Solid Infill vs. Thick Walls

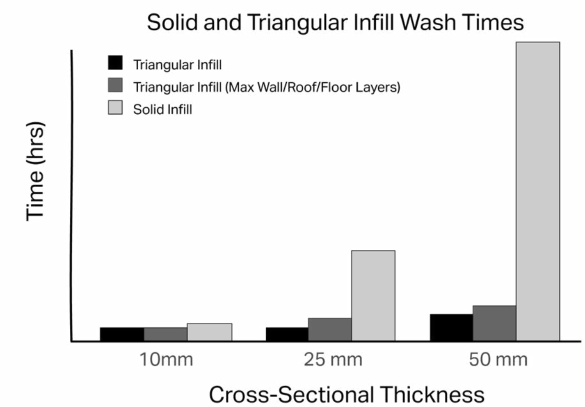
Print settings will also impact washing and drying times. Thicker walls and floors take longer to dry than standard triangular infill parts, but solid infill parts take considerably longer than either; Eiger accounts for part thickness and infill when estimating wash times. When planning solid infill part production, always account for the extended wash/dry cycle in your timeline.

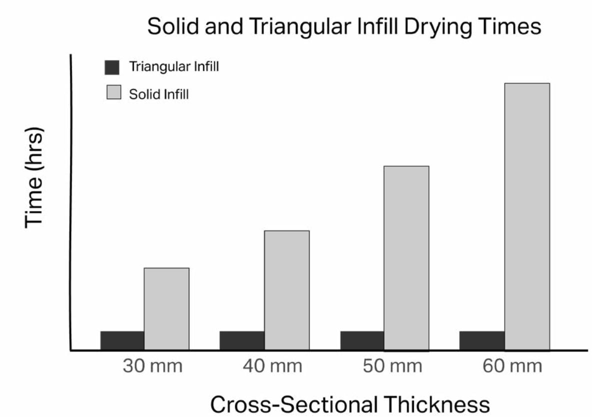
Wash times are heavily dependent on the thickest cross-sectional area feature of a green part. The Wash Time graph at right provides an overview of how the cross-sectional area of standard triangular infill parts will impact your workflow compared to non-default settings. Solid infill parts will drastically increase wash times as this area increases.

The graph at lower right shows how the drying time is impacted by deviating from default settings. Drying time for triangular infill parts is independent of part dimension; however, selecting solid infill can significantly increase drying times, particularly for larger parts.

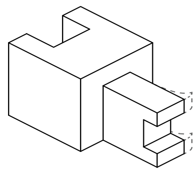
For more information on the washing process, please see our support documentation.

(Note that these graphs are not to scale. Always follow the wash and drying times provided by Eiger.)

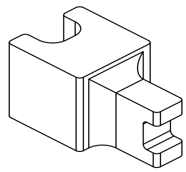




Optimize For Sintering



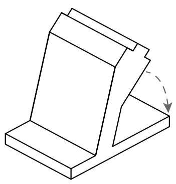
Sharp edges may cause deformation during sintering



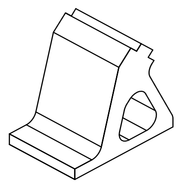
Smooth transitions reduce deformation

Reduce Stress Concentrations

Parts undergo thermal stresses when sintering because they pull themselves together as they shrink. Reduce stress concentrations by filleting your edges and designing gradual changes in thickness.



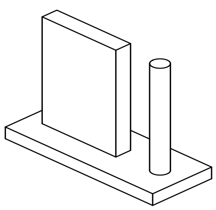
Cantilevered features may topple when sintered



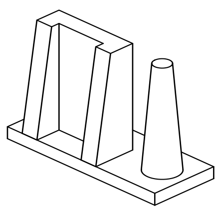
Balanced features stay supported during sintering

Ensure Features are Well Balanced

As parts go through the sintering process, the heat induces a clay-like state that makes them malleable. If your parts don't need supports, ensure they are inherently stable in their printed orientation. Avoid top-heavy, cantilevered, or tall and thin features.



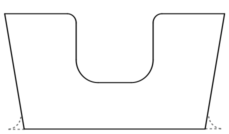
Tall standalone features can lean or topple during sintering



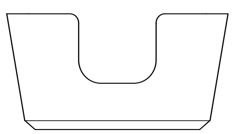
Ribs and draft angles provide inherent stability

Support Freestanding Features

Tall, thin features more than six times their height may lean or topple during sintering. Support freestanding features by adding draft angles or ribs to increase their strength and inherent stability during sintering.



Straight bottom edges can splay out during sintering



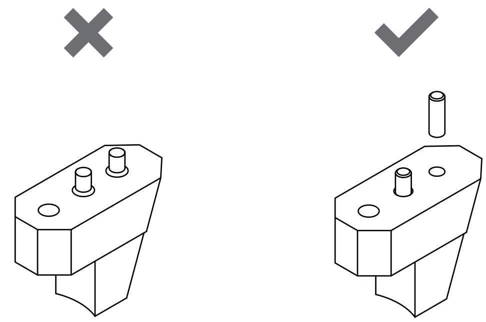
Splaying avoided with chamfered bottom edge

Chamfer Bottom Edges

The bottom edge of your part may splay out during sintering. Adding a 0.5-1.0 mm (0.02"-0.04") chamfer to the bottom edges of your part will prevent splayed edges, especially on small features like holes and channels.

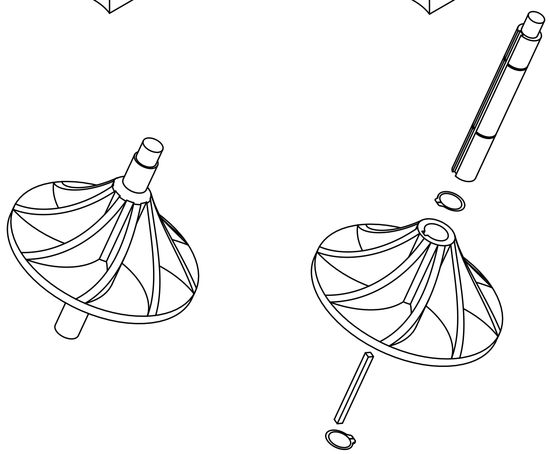
Strategic Metal Printing Practices

Think critically about what aspects of your design need to be 3D printed. Some features could be implemented more efficiently with other manufacturing methods. When appropriate, integrate other parts into your design to save on print time, design complexity, and cost. Below are some examples:



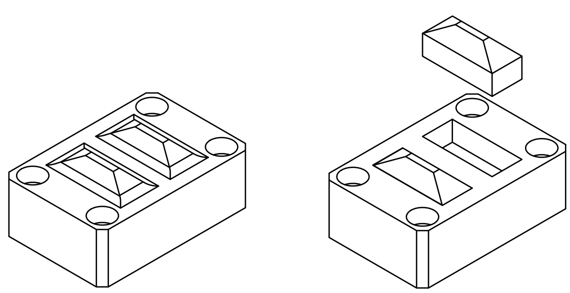
Use Pins for Alignment Features

Improve alignment precision and save material and print time by pressing dowel pins into your parts or using shoulder bolts for location. Dowel pins pressed into this gripper jaw locate it on a robotic arm. This design change reduces supports and simplifies print orientation.



Separate Printed from Simple Features

Isolate complex part features for metal 3D printing. Printing an impeller with an integrated shaft will sacrifice optimal print orientation for furnace orientation — it can only fit in the Sinter-1 sideways. Instead, the impeller can be printed apart from a turned shaft to decrease print time and part complexity. The retaining rings locate the impeller on the shaft, and the key acts as a shear point that can be swapped if it fails.

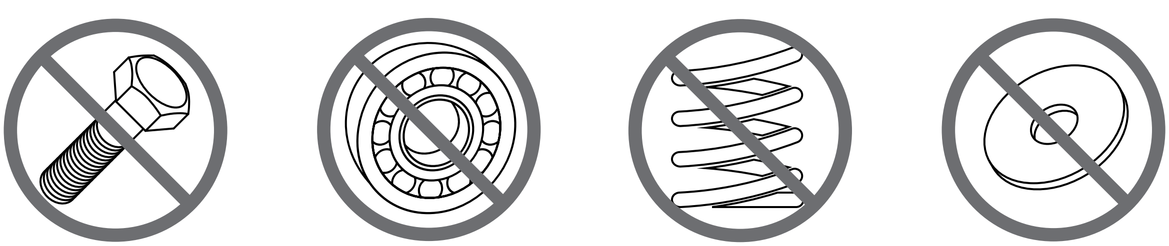


Isolate Properties with Modular Features

This sheet metal stamp consists of a blank with metal printed inserts. Isolating the metal inserts as separate parts localizes metal properties to only the region they are required, so you don’t need to print an entirely new tool for every revision. This also makes maintenance and tool repair easy.

DON’T PRINT YOUR HARDWARE

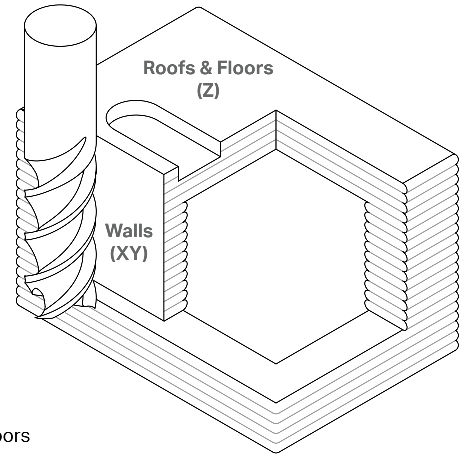
Printing hardware is a poor use of the Metal X — purchasing off-the-shelf hardware is almost always more cost- and time-efficient and produces better results. Hardware like bushings, bearings, and springs are produced with specialized manufacturing processes and will not behave the same way when printed. Washers, nuts, bolts, and similar hardware are cheaper and more effective to purchase than to print.



Post-Processing Metal Parts

Machining and Polishing Sintered Parts

If you intend to machine or polish your parts post-sintering, we highly recommend increasing the wall thickness of your part, which will give you more room to face your parts. Use the table below to find the ideal amount of material to remove. Don't remove more than the stated wall thickness, or you will cut through the shells and expose infill. Tool Steels must be annealed before machining.



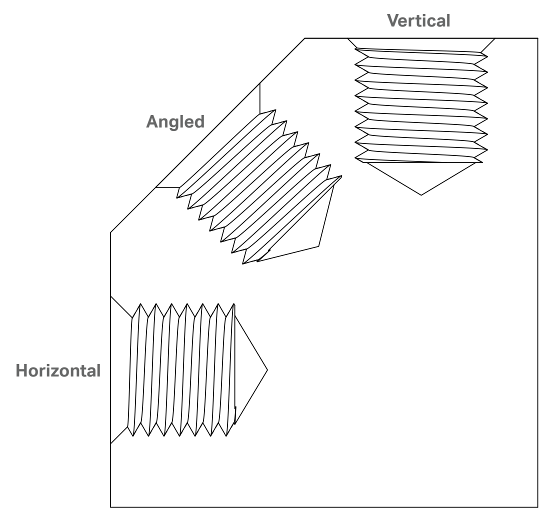
Shell Setting	Shell Thickness		Recommended Removal	
	Walls	Roofs/Floors	Walls	Roofs/Floors
Default	1.0 mm (0.039")	0.5 mm (0.020")	0.3±0.15 mm (0.12±0.005")	0.2± 0.1 mm (0.08±0.004")
Recommended for Machinability	1.5 mm (0.059")	1.5 mm (0.059")	0.5±0.2 mm (0.02±0.008")	0.5±0.2 mm (0.02±0.008")

Do not remove more than half the shell thickness or it will compromise part strength.
Eiger allows you to increase the shell thickness up to a maximum of 2.01 mm.

Threads

Use the table below to identify what kinds of threaded holes should be tapped or printed when designing your part. Use 50% thread engagement to size tapped holes. Printed threads may need to be chased with a tap, or need lapping compounds for an even thread.

Thread Size	Thread Orientation	Recommendation
< M3 *(or < #5-40)*	Vertical Angled or Horizontal	Tap Tap
M3-M8 *(or #5-40 to 5/16"-18)*	Vertical Angled or Horizontal	Tap or Print Tap
M8-M10 *(or 5/16"-18 to 3/8"-16)*	Vertical Angled or Horizontal	Tap or Print Print
> M10 *(or > 3/8"-16)*	Vertical Angled or Horizontal	Print Print



Green-State Sanding

Wet sanding green parts under warm water with 240-320 grit sandpaper or Scotch-Brite leaves a matte finish once sintered. Green parts are fragile, so be cautious as any modifications may affect precision or sintering performance. Sand over a receptacle or filter to prevent sink clogging, and use proper PPE.

Some metal printed parts may be difficult to fixture for machining or tapping due to their complex geometry. You can use Markforged composite printers to create conformal workholding to hold the metal parts in these cases.

Material Selection

With a growing list of printable metals, how do you choose the right one? List out the part's functional requirements, and that will lead you to an optimal material for the job. What environment will the part operate in? What will it come in contact with, and how? What behavior should it exhibit under stress or heat? Answer these questions to help select the material you need.

Stainless Steels

Stainless steels are versatile metals characterized by their excellent uniform corrosion resistance, high strength, and good finish. Because of their high chromium content and low carbon content, they are low maintenance and easy to weld.

17-4 PH Stainless Steel is a common martensitic stainless steel, and can be precipitation hardened to adjust mechanical properties to fit your application. This makes 17-4 PH an incredibly versatile material that can be tuned for a variety of applications, including metalworking, aerospace, petrochemical, and medical industries.

316L Stainless Steel (Coming Soon) is an austenitic stainless steel with boosted localized corrosion resistance, in addition to what many stainless steels already have. This makes it well suited for marine and chemical handling applications, and its low carbon content (below 0.03%) means it is easy to weld without weld corrosion.

Tool Steels

These steels are optimized for cutting and forming other materials, meaning they are typically abrasion resistant, hard, and tough. Each class of tool steel is optimized to work with certain types of materials and applications.

A2 Tool Steel is a general-use, versatile tool steel that balances wear resistance and toughness. It performs well for typical cold work impact- or forming-based tooling applications such as stamping, punching, and metal bending.

D2 Tool Steel is a tool steel best known for its wear resistance and hardness in cold-work applications. It can be sharpened and heat treated to boost its hardness and hold an edge, and can be used for cutting tool applications.

H13 Tool Steel is a hot-work class steel optimized for its high temperature hardness and abrasion resistance. This makes it a great fit for high temperature molding applications like inserts, cores, and dies. It is resistant to thermal fatigue and premature heat-checking, and has excellent through-hardening properties.

Superalloys

Superalloys are high-performance alloys with excellent mechanical strength and stability at high temperatures. These alloys are also highly corrosion resistant, often used in harsh environments, and exposed to extreme heat or chemicals.

Inconel 625 is well suited for high-heat and -pressure environments because it maintains its strength over a wide range of temperatures. Combined with its corrosion resistance, it is well suited for petrochemical applications.

Non-Ferrous Metals

Non-ferrous metals have little to no iron in their molecular makeup, and often have a range of useful properties depending on the metal and application. Many non-ferrous metals are lightweight, conductive, and easy to work with.

Copper is a ductile metal known for its high electrical and thermal conductivity, making it very useful for applications requiring the transfer of current or dissipation of heat, including busbars, heat exchangers, and heat sinks.

Titanium 6Al-4V (Coming Soon) is very lightweight while incredibly strong and stiff — resulting in a best-in-class strength-to-weight ratio. It has excellent corrosion resistance, which combined with its light weight make it an excellent choice for vehicles and biomedical equipment.

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Heat Treatment

Heat treatment is a process commonly applied to certain steels to manipulate their material properties. Markforged recommends a double heat-treat on all tool steels to minimize distortion in complex parts. Specific properties may vary depending on part size and complexity. For more specific details, reference our data sheet or other treatment guides.

If you plan on post-machining tool steel printed parts, you must anneal them beforehand.

17-4 PH Stainless Steel

Heat Treatment Information

Post-sintered 17-4 PH Stainless Steel is in a near-annealed state that can be easily worked with. Annealing to Condition A is only necessary if a part needs re-treatment.

Heat Treatment: Heat the part to the temperature and for the time span listed in the table to the right based on the desired condition. Post-sintered 17-4 does not need annealing prior to treatment. All parts should be air cooled.

Condition	Heat To *°F (°C)*	Time at Temp.	Yield Strength *MPa*	Elongation *% in 2"*	Hardness *Rc*
A	1950 (1066)	30 min	760	5	34
H900	900 (482)	1 hr	1170	10	40
H925	925 (496)	4 hrs	1070	10	38
H1025	1025 (551)	4 hrs	1000	12	35
H1075	1075 (580)	4 hrs	860	13	32
H1100	1100 (593)	4 hrs	795	14	31
H1150	1150 (621)	4 hrs	725	16	28
H1150-M	1400 (760) *followed by* 1150 (621)	2 hrs *followed by* 4 hrs	520	18	24

Material data reflects typical values for wrought materials. Printed part properties may differ.

A2 Tool Steel

Heat Treatment Information

1. Anneal: Heat the part to 1550-1600°F (843-871°C) at 400°F (222°C) per hour and hold at temperature for one hour per inch of maximum part thickness, with a two-hour minimum. Cool slowly at a rate not exceeding 50°F (28°C) per hour until 1000°F (538°C), then continue cooling in air.

2. Preheat: Heat the part at 400°F (222°C) per hour to 1150-1250°F (621-677°C) and let the part equalize, then heat to 1300-1400°F (704-760°C) and equalize again.

3. Austentize: Heat slowly from preheat to 1725-1750°F (941-954°C) and hold for 30 minutes for the first inch of thickness, with an additional 15 minutes per additional inch.

4. Quench: Quench the part in air, pressurized gas, or interrupted oil to below 150°F (65°C). Larger parts will not achieve full hardness in still air, so a gas or oil quench may be needed. Use a vacuum or controlled atmosphere furnace to avoid scaling.

5. Temper: Temper immediately after quenching to the temperature listed based on desired hardness. Hold at temperature for one hour per inch of maximum part thickness or at least two hours, whichever is longer.

Temper To *°F (°C)*	Hardness *Rc*
300 (149)	62
400 (204)	60
500 (260)	58
600 (316)	56
700 (371)	56
800 (427)	56
900 (482)	56
1000 (538)	55
1100 (593)	50
1200 (649)	43
1300 (704)	34
As Sintered	52

Material data reflects typical values for wrought materials. Printed part properties may differ.

The following were referenced in creating these guides:

17-4 PH Stainless Steel:

ASTM A 564/A 564M: *Standard Specification for Hot-Rolled and Cold-Finished Age-Hardening Stainless Steel Bars and Shapes*

Specialty Steel Supply: *specialtysteelsupply.com/brochure/17-4-technical-data.pdf*

AK Steel: *aksteel.com/sites/default/files/2018-01/174ph201706.pdf*

A2 Tool Steel:

ASTM A681: *Standard Specification for Tool Steels Alloy*

Hudson Tool Steel: *hudsontoolsteel.com/technical-data/steelA2*

Speedy Metals: *speedymetals.com/information/Material69.html*

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Heat Treatment

D2 Tool Steel

Heat Treatment Information

1. Anneal: Heat the part to 1550-1600°F (843-871°C) at 400°F (222°C) per hour and hold at temperature for one hour per inch of maximum part thickness, with a two-hour minimum. Cool slowly at a rate not exceeding 50°F (28°C) per hour until 1000°F (538°C), then continue cooling in air.

2. Preheat: Heat the part at 400°F (222°C) per hour to 1150-1250°F (621-677°C) and let the part equalize, then heat to 1400-1450°F (760-788°C) and equalize again.

3. Austentize: Heat slowly from preheat to 1850-1875°F (1010-1024°C) until uniformly heated.

4. Quench: Quench the part in air or pressurized gas to below 150°F (65°C). Use a vacuum or controlled atmosphere furnace to avoid scaling.

5. Temper: Temper immediately after quenching to the temperature listed based on desired hardness. Hold at temperature for one hour per inch of maximum part thickness or at least two hours, whichever is longer.

Temper To *°F (°C)*	Hardness *Rc*
As Quenched	64
400 (204)	60
500 (260)	58
600 (316)	58
700 (371)	58
800 (427)	57
900 (482)	57
1000 (538)	56
1100 (593)	48
1200 (649)	40
1300 (704)	34
As Sintered	54

Material data reflects typical values for wrought materials. Printed part properties may differ.

H13 Tool Steel

Heat Treatment Information

1. Anneal: Heat the part to 1553-1652°F (845-900°C) at 400°F (222°C) per hour and hold at temperature for one hour per inch of maximum part thickness, with a two-hour minimum. Cool slowly at a rate not exceeding 50°F (28°C) per hour until 1000°F (538°C), then continue cooling in air.

2. Preheat: Heat the part at 400°F (222°C) per hour to 1100-1250°F (593-677°C) and let the part equalize, then heat to 1500-1600°F (816-871°C) and equalize again.

3. Austentize: Heat rapidly to 1800-1890°F (982-1032°C) and hold for 30 minutes to two hours. Use a salt bath or controlled atmosphere furnace to minimize decarburization.

4. Quench: Quench the part in still air. Temper immediately after quenching. You may use an interrupted oil quench to below 150°F (65°C) on large parts or to maximize hardness and toughness, but there is some risk of cracking during the process.

5. Temper: Temper at a minimum of 50°F (28°C) above the maximum operating temperature of the part, using the table to the right as a guide. Temper at one hour per inch of maximum part thickness or at least two hours, whichever is longer. A second temper at 25-50°F (14-28°C) below the first is recommended, especially when heat checking is a problem.

Temper To *°F (°C)*	Hardness *Rc*
900 (482)	54
1000 (538)	52
1050 (566)	50
1100 (593)	46
1150 (621)	36
1200 (649)	30
As Sintered	40

Material data reflects typical values for wrought materials. Printed part properties may differ.

The following were referenced in creating these guides:

D2 Tool Steel:

ASTM A681: *Standard Specification for Tool Steels Alloy*

Speedy Metals: *speedymetals.com/information/Material11.html*

Hudson Tool Steel: *hudsontoolsteel.com/technical-data/steelD2*

H13 Tool Steel:

ASTM A681: *Standard Specification for Tool Steels Alloy*

Hudson Tool Steel: *hudsontoolsteel.com/technical-data/steelH3*

Cincinnati Tool Steel Company: *cintool.com/documents/mold_quality/H13.pdf*

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