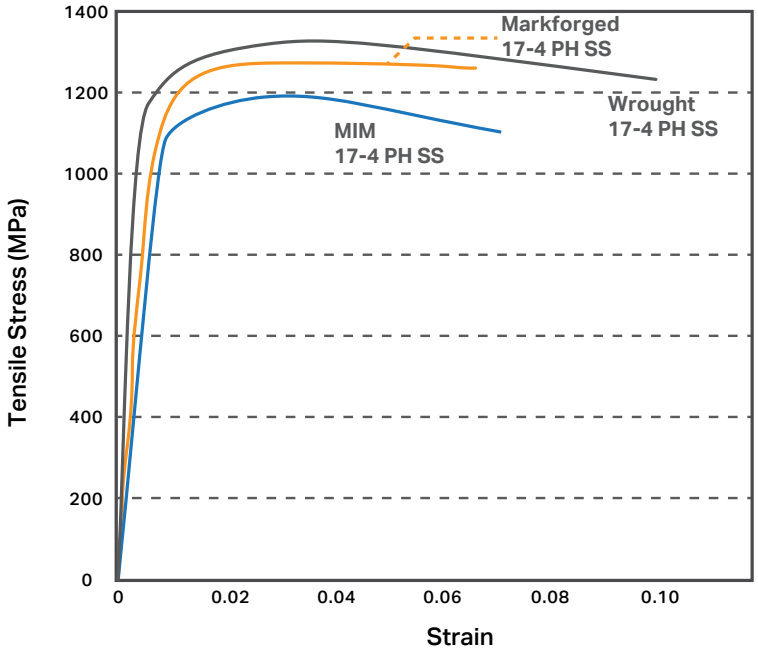
MATERIAL DATASHEET

17-4 PH Stainless Steel

Markforged

Composition	Amount
Chromium	15-17.5%
Nickel	3-5%
Copper	3-5%
Silicon	1% max
Manganese	1% max
Niobium	0.15-0.45%
Carbon	0.07% max
Phosphorous	0.04% max
Sulfur	0.03% max
Iron	bal



Markforged H900 Heat Treated

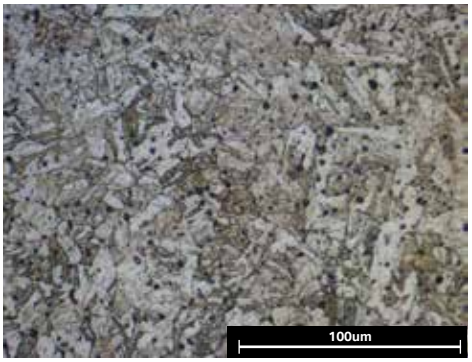
17-4 PH stainless steel processed with the Markforged Metal X system heat treated to H900 specification.

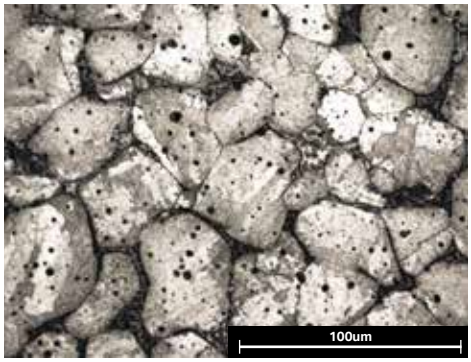
MIM H900 Heat Treated

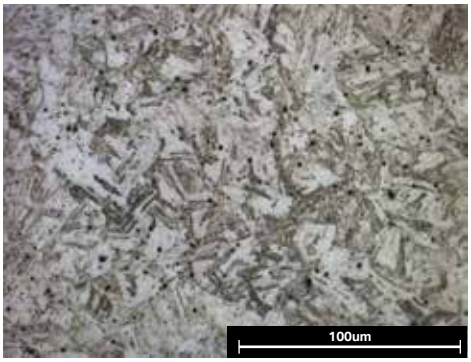
17-4 PH MIM standard stainless steel heat treated to H900 specification.

ASTM A564 H900 Heat Treated

ASTM A564 17-4 PH stainless steel heat treated to H900 specification.







Typical Mechanical Properties	Standard	Markforged H900	MIM H900	ASTM A564 H900
Ultimate Tensile Strength	ASTM E8	1250 MPa	1190 MPa	1310 MPa
0.2% Yield Strength	ASTM E8	1100 MPa	1090 MPa	1170 MPa
Elongation at Break	ASTM E8	6%	6%	10%
Tensile Modulus	ASTM E8	170 GPa	190 GPa	190 GPa
Hardness	ASTM E18	36 HRC	33 HRC	40 HRC
Corrosion	ASTM F1089	Pass	Pass	Pass
Relative Density	ASTM B923	96%	95.5%	100%

All data and graphs on front page reflect values of H900 heat treated 17-4 PH SS. Markforged represent typical tested values, while MIM H900 and Wrought H900 represent typical reference values from MPIF Standard 35. For values of Markforged printed 17-4 PH SS as-sintered and with H1150 heat treatment, please see the reverse side. All composition and "As-Sintered" data verified by a third party test facility. All microstructure images etched and photographed at Markforged.

ADDITIONAL DATA

17-4 PH Stainless Steel

Markforged

Values listed below compare Markforged samples processed in three different ways: As-Sintered, heat treated to H900 standard, and heat treated to H1150 standard.

Typical Mechanical Properties	Standard	As Sintered	H900	H1150
Ultimate Tensile Strength	ASTM E8	1050 MPa	1250 MPa	950 MPa
0.2% Yield Strength	ASTM E8	800 MPa	1100 MPa	880 MPa
Elongation at Break	ASTM E8	5%	6%	10%
Tensile Modulus	ASTM E8	140 GPa	170 GPa	170 GPa
Hardness	ASTM E18	30 HRC	36 HRC	32 HRC
Corrosion	ASTM F1089	Pass	Pass	Pass
Relative Density	ASTM B923	96%	96%	96%

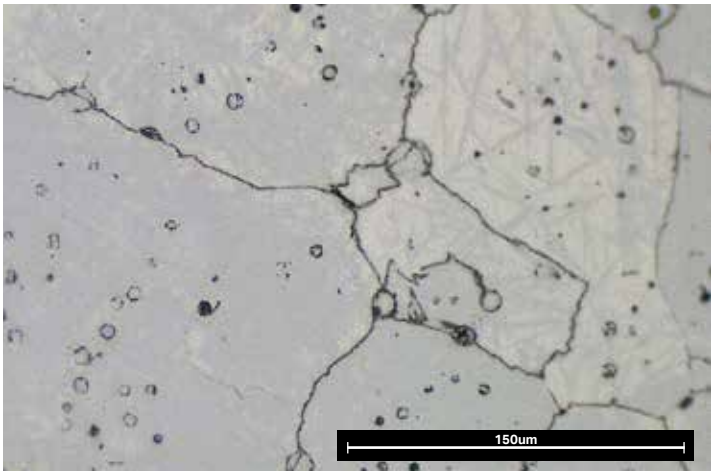
MATERIAL DATASHEET

A2 Tool Steel

Other Designations: UNS T30102, DIN 1.2363 , X100CrMoV5, SKD12, BA2

A2 tool steel is a highly versatile air-hardening tool steel often regarded as a “universal” cold work steel. It offers a combination of good wear resistance (between O1 and D2) and toughness. Considered relatively easy to machine in the annealed condition, it has a high compression strength and good dimensional stability during hardening and tempering. It’s used for a wide variety of cold-work tools, from forming and cutting equipment to high wear parts.

Composition	Amount
Chromium	4.75-5.5%
Molybdenum	0.9-1.4%
Carbon	0.95-1.05%
Manganese	0.4-1%
Phosphorus	0.3% max
Vanadium	0.15-0.5%
Silicon	0.1-0.5%
Iron	bal



Typical Mechanical Properties	Standard	Markforged As-Sintered[3]	Markforged Heat-Treated[1]	Wrought Heat Treated
0.2% Compressive Yield Strength	ASTM E9	up to 900 MPa	1170 MPa	—
Elastic Modulus	ASTM E9	180 GPa	160 GPa	190 GPa
Hardness	ASTM E18	up to 50 HRC	50 HRC	63 HRC
Relative Density[4]	ASTM B923	94.5%	94.5%	100%

Heat Treatment

A2 tool steel can be heat-treated to increase hardness and durability. Markforged recommends heat-treating A2 tool steel to optimize material properties, though it can be used as-sintered.

1. Heat A2 Tool Steel part in a standard (non vacuum) furnace to 970°C (1780°F) . Hold part at temperature for 30-45 minutes.
2. Air quench part to below 65°C (150 °F).
3. Double temper A2 Tool Steel part in a standard furnace. For each temper, heat part to 150-550°C[2] (302-1022°F) and temper for 2 hours, or 1 hour per inch of thickness. If double tempering, let part cool to room temperature between tempers.

1. Markforged heat-treated A2 tool steel was heated to 970°C (1780°F) and single tempered at 200°C (392°F) for 30 minutes.
2. Tempering temperature has a significant effect on final material properties. For higher hardness, temper at low temperatures. For higher toughness, temper at higher temperatures.
3. As-sintered hardness can vary significantly based on furnace loading and ambient environment. Markforged recommends post-sinter heat treatment for maximum hardness and compression strength.
4. Relative density for A2 assumes a density of 7.86 g/cm3.

These data represent typical values for Markforged A2 Tool Steel as-sintered. Markforged samples were printed with solid fill. Relative density and as-sintered hardness was tested in house. All other data were tested and confirmed by outside sources. These representative data were tested, measured, or calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.

MATERIAL DATASHEET

Copper

Markforged

Copper is a soft, ductile metal used primarily for its electrical and thermal conductivity. Copper's high conductivity makes it an ideal material for many heat sinks and heat exchangers, power distribution components such as bus bars, manufacturing equipment including spot welding shanks, antennae for RF communications, and more. The ability to print pure copper using Metal X enables geometrically optimized parts that were previously expensive, time consuming, or impossible to make.

Composition	Amount
Copper	99.8% min
Oxygen	0.05% max
Iron	0.05% max
Other	bal

Typical Mechanical Properties	Standard	Temp	Markforged As-Sintered	MIM Standard
Ultimate Tensile Strength	ASTM E8	Room Temp	193 MPa[1]	207 MPa
0.2% Tensile Yield Strength	ASTM E8	Room Temp	26 MPa[1]	69 MPa
Elongation at Break	ASTM E8	Room Temp	45%[1]	30%
Relative Density	ASTM B923	Room Temp	98%[2]	98%
Electrical Conductivity	ASTM E1004	Room Temp	84% IACS[3]	—
Thermal Conductivity	ASTM E1461	Room Temp	350 W/mK[4]	328 W/mK
Coefficient of Thermal Expansion	ASTM E831-19[5]	68-100°F	9.6 x 10^{-6}/°F	8.7 x 10^{-6}/°F
	ASTM E228	68-150°F	9.7 x 10^{-6}/°F	8.9 x 10^{-6}/°F
		68-200°F	9.8 x 10^{-6}/°F	9.1 x 10^{-6}/°F
		68-250°F	9.9 x 10^{-6}/°F	9.3 x 10^{-6}/°F
		68-300°F	10.0 x 10^{-6}/°F	9.4 x 10^{-6}/°F
		68-500°F	10.1 x 10^{-6}/°F	—
		68-750°F	10.5 x 10^{-6}/°F	—

1. Tensile bars are sub-sized and are sliced with default copper settings except raft is turned off. Copper defaults to solid parts.
2. Density is based on a theoretical value of 8.96g/cc.
3. Electrical conductivity, when evaluated with eddy current instruments, is usually expressed as a percentage of the conductivity of the International Annealed Copper Standard (% IACS). The conductivity of the Annealed Copper Standard is defined to be 0.58 × 108 S/m (100 % IACS) at 20°C.
4. Thermal diffusivity measured per ASTM E1461. Diffusivity was converted to Conductivity using, Thermal Conductivity = Thermal Diffusivity * Density * Specific Heat. Assuming specific heat of Copper = 0.385 J/g-K per "Handbook of Chemistry and Physics 72nd Edition."
5. Markforged as-sintered Coefficient of Thermal Expansion (CTE) was measured by a 3rd party lab using Thermal Mechanical Analysis (ASTM E831). The MIM handbook reference used a Push Rod Dilatometer (ASTM E228)

These data represent typical values for Markforged Copper as-sintered. Markforged samples were printed with Solid Infill setting. All values based on 3rd party testing except for relative density which was tested by Markforged. These representative data were tested, measured, and calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.

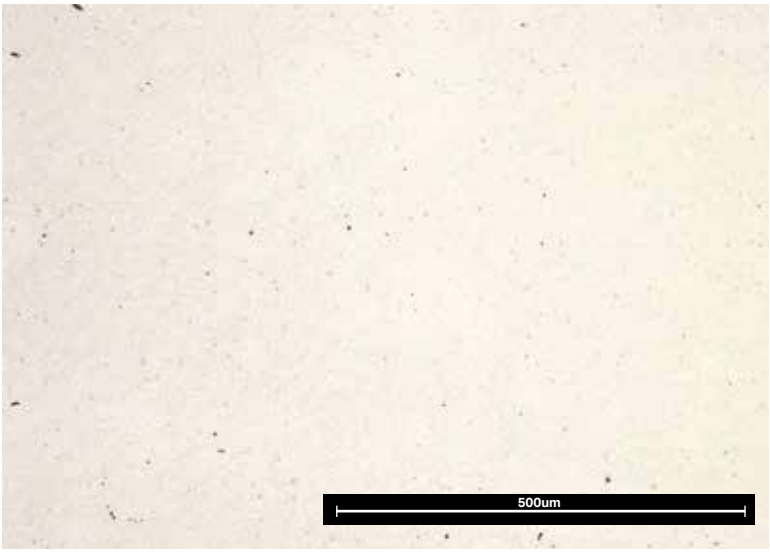
MATERIAL DATASHEET

D2 Tool Steel

Other Designations: DIN 12379, ASTM A681, UNS T30402, BD 2

D2 tool steel is a high carbon, high chromium air-hardening tool steel that can be heat treated to high hardness and compressive strength. D2 offers excellent wear resistance and is widely used in cold work applications that require sharp edges, abrasion resistance, and compressive strength. Markforged D2 meets chemical requirements of ASTM A681.

Composition	Amount
Chromium	11-13%
Carbon	1.4-1.6%
Molybdenum	0.7-1.2%
Vanadium	0.5-1.1%
Nickel + Copper	0.75% max
Manganese	0.1-0.6%
Silicon	0.1-0.6%
Phosphorus	0.03% max
Sulfur	0.03% max
Iron	bal



Typical Mechanical Properties	Standard	Markforged As-Sintered	Markforged Heat-Treated[1]	Wrought Heat Treated[2]
0.2% Compressive Yield Strength	ASTM E9	830 MPa	1690 MPa	2200 MPa
Elastic Modulus	ASTM E9	170 GPa	187 GPa	210 GPa
Hardness[3]	ASTM E18	54 HRC	60 HRC	62 HRC
Relative Density[4]	ASTM B923	97%	97%	100%

Heat Treatment

D2 tool steel can be heat-treated to increase hardness and durability after an optional annealing step and machining work. Markforged recommends heat-treating D2 tool steel to optimize material properties, though it can be used as-sintered.

1. Heat D2 Tool Steel part in a standard (non-vacuum) furnace to 1000°C (1830°F) . Hold part at temperature for 30-45 minutes.
2. Air quench part to below 65°C (150 °F).
3. Temper D2 Tool Steel part in a standard furnace. For each temper, heat part to 200°C[5] (392°F) and temper for 30 minutes. If double tempering, let part cool to room temperature between tempers.

1. Markforged heat-treated D2 tool steel was heated to 970°C (1780°F) and single tempered at 200°C (392°F) for 30 minutes.
2. Wrought heat treatment data from Bohler-Uddeholm: http://cdna.terasrenki.com/ds/1.2379_X153CrMoV12_AISI-D2_SS-2310_Datasheet_2.pdf
3. Markforged hardness was measured on a sample coupon that was printed at 100% infill and has a 25 mm diameter and 10 mm height.
4. Relative density for D2 assumes a density of 7.7 g/cm^2.
5. Tempering temperature has a significant effect on final material properties. For higher hardness, temper at low temperatures. For higher toughness, temper at higher temperatures.

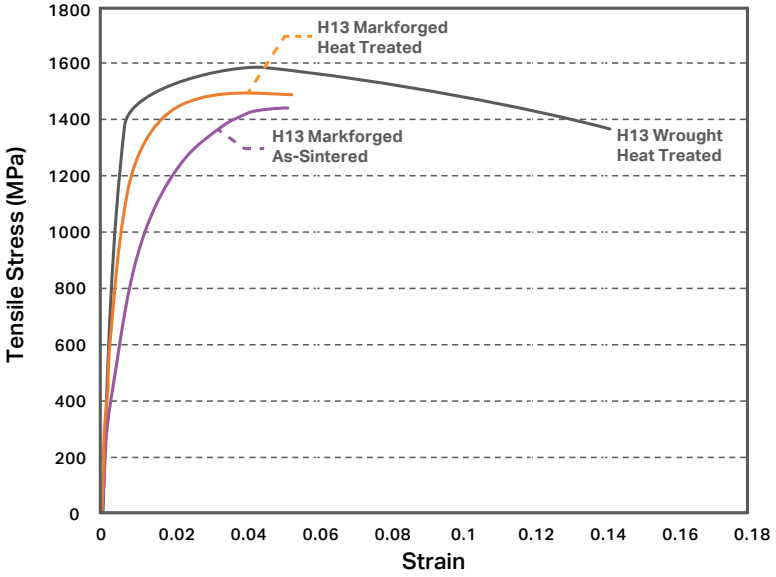
These data represent typical values for Markforged D2 Tool Steel as-sintered. Markforged samples were printed as fully dense parts with 100% infill. Hardness and density data were tested in house, and all other data were tested and confirmed by outside sources. These representative data were tested, measured, or calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.

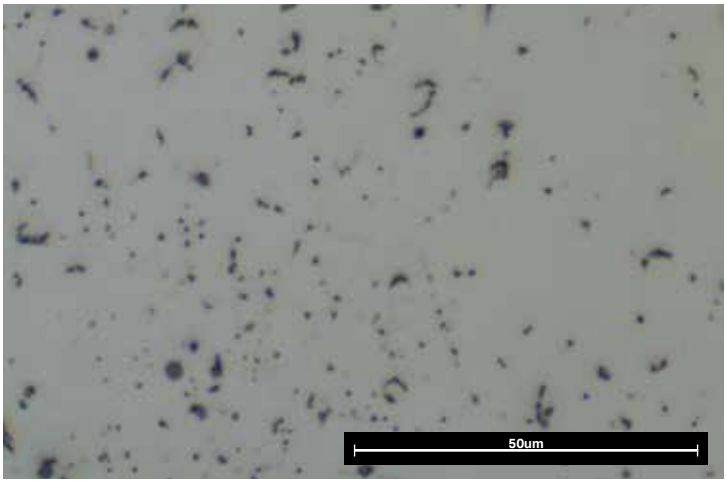
MATERIAL DATASHEET

H13 Tool Steel

Markforged

Composition	Amount
Chromium	4.7-5.5%
Molybdenum	1.3-1.7%
Silicon	0.8-1.2%
Vanadium	0.8-1.2%
Carbon	0.3-0.45%
Manganese	0.2-0.5%
Phosphorous	0.03% max
Sulfur	0.03% max
Iron	bal





Markforged H13 As-Sintered

H13 Tool Steel printed on the Metal X, washed in the Wash-1, and sintered in the Sinter-1. As Sintered Microstructure is pictured to the left.

Markforged H13 Heat Treated

H13 Tool Steel printed with the Metal X system, air quenched at 1010C, and double tempered at 600C

Wrought H13 Heat Treated

Wrought H13 tool steel standard from *ASM Specialty Handbook* - air quenched at 1010C and double tempered at 600C.

Typical Mechanical Properties	Standard	Markforged As-Sintered	Markforged Heat Treated	Wrought Heat Treated*
Ultimate Tensile Strength	ASTM E8	1420 MPa	1500 MPa	1580 MPa
0.2% Yield Strength	ASTM E8	800 MPa	1250 MPa	1360 MPa
Elongation at Break	ASTM E8	5%	5%	14%
Hardness	ASTM E18	40 HRC	45 HRC	46 HRC
Relative Density	—	≥ 94.5%	≥ 94.5%	100%

These data represent typical values for Markforged H13 Tool Steel as-sintered and after heat treatment. Values were tested in house, and both material composition and "As-Sintered" data were confirmed by outside testing. These representative data were tested, measured, or calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.
*Wrought Heat Treated data included in table only. Data from *ASM Specialty Handbook: Tool Materials* page 140

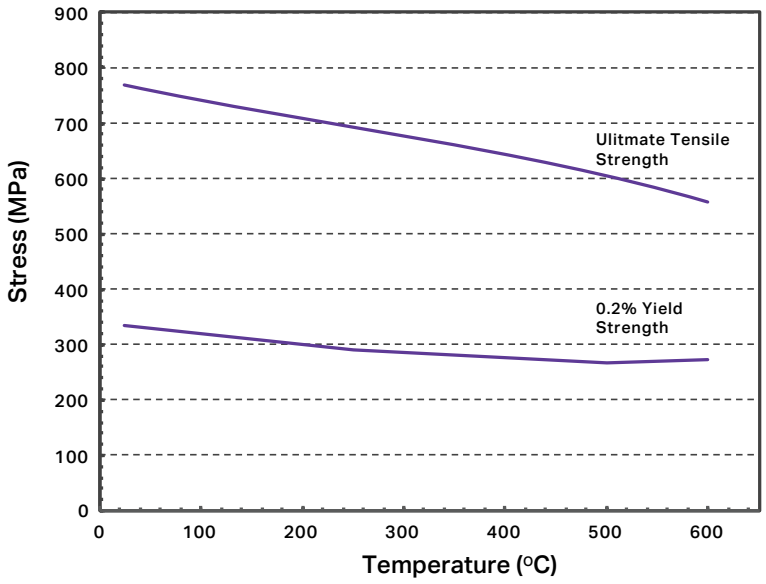
MATERIAL DATASHEET

Inconel 625

Other Designations: UNS N06625, ISO NW6625, DIN 17744

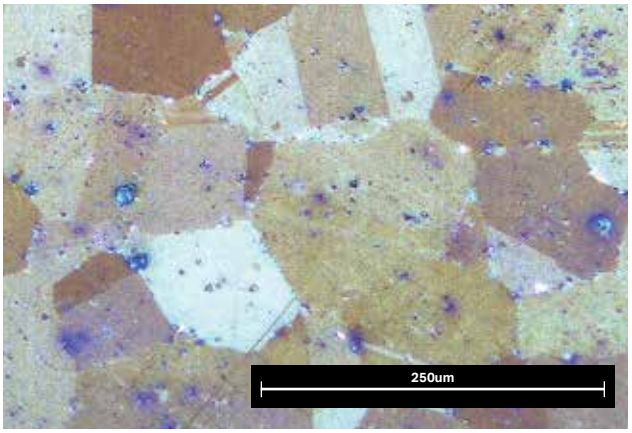
Inconel 625 is a nickel-chromium based superalloy that is highly resistant to corrosion and high temperatures. It's easy to print; allowing you to make functional prototypes and end-use parts for harsh environments. Markforged Inconel 625 meets chemical requirements of ASTM B443.

Composition	Amount
Chromium	20-23%
Molybdenum	8-10%
Iron	5% max
Niobium	3.15-4.15%
Cobalt	1% max
Manganese	0.5% max
Silicon	0.5% max
Aluminum	0.4% max
Titanium	0.4% max
Carbon	0.1% max
Phosphorus	0.015% max
Sulfur	0.015% max
Nickel	bal



Markforged Inconel 625 As-Sintered

Inconel 625 printed on the Metal X, washed in the Wash-1, and sintered in the Sinter-1. As-Sintered microstructure captured at 100x is pictured to the right.



Typical Mechanical Properties	Standard	Markforged As-Sintered	Wrought AMS 5599[1]
Ultimate Tensile Strength	ASTM E8	765 MPa	827 MPa
0.2% Yield Strength	ASTM E8	334 MPa	414 MPa
Elongation at Break	ASTM E8	42%	30%
Hardness	ASTM E18	7 HRC	0-19 HRC
Relative Density[2]	ASTM B923	96.5%	100%

1. Wrought AMS 5599 data represent minimum values, except for Hardness.
2. Relative density for Inconel 625 assumes a reference density of 8.44 g/cm^2.
3. ASTM E21 elevated temperature testing was conducted by 3rd party NADCAP lab. Samples were printed in XY and gauge length was machined to size.

These data represent typical values for Markforged Inconel 625 as-sintered. Markforged samples were printed as fully dense parts with 100% infill. Hardness and density data were tested in house, and all other data were tested and confirmed by outside sources. These representative data were tested, measured, or calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.