COLIBRIUM ADDITIVE
a GE Aerospace company

13 Al

22 Ti | 24 Cr | 26 Fe | 27 Co | 28 Ni | 29 Cu

L-PBF Ti6Al4V Grade 23

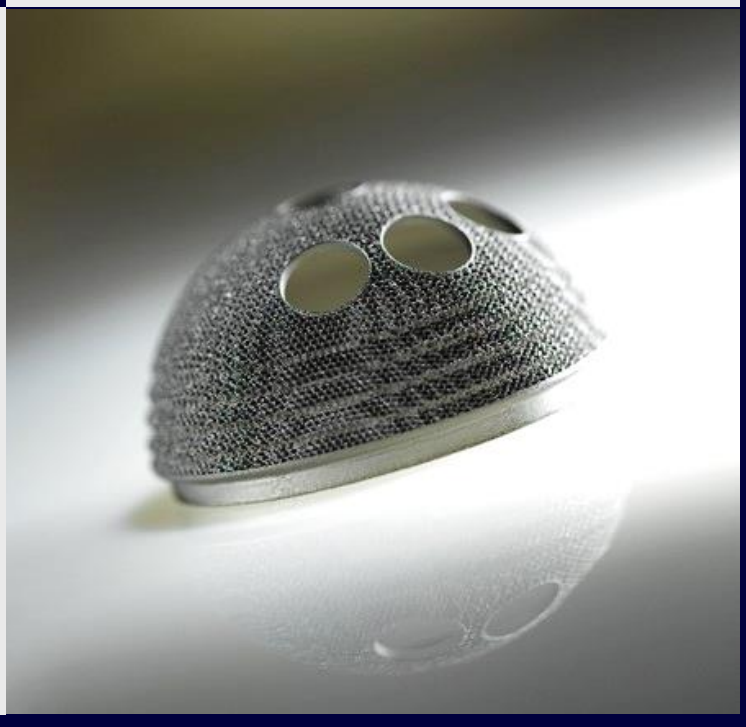
Parameters for Colibrium Additive's M2 Series 5

Titanium Ti6Al4V Grade 23 (ELI)

Ti6Al4V Grade 23, renowned for its exceptional strength-to-weight ratio, is ideal for additive manufacturing. It offers outstanding biocompatibility, making it perfect for medical implants. Its superior corrosion resistance ensures longevity and reliability in demanding environments. This alloy is widely used in the aerospace industry for critical components, in the medical field for durable implants, and in high-performance motorsports for lightweight, robust parts. Its versatile properties make Ti6Al4V Grade 23 a preferred choice across these advanced industries.

M2 Series 5 Ti6Al4V

The parameters for the Colibrium Additive M2 Series 5 are designed to meet a wide range of customer specifications. The surface parameter is a 30 µm parameter that produces the best surface roughness, having less than 10 µm without the need of bead blasting or shot peening. The balanced parameter has a layer thickness of 60 µm and provides nearly double the productivity of the surface parameter, but still offers very good surface quality. Exceptional high productivity, reaching 61 cm^3/h for a dual-laser system, can be reached by the productivity parameter having a layer thickness of 120 µm. All parameters have outstanding tensile properties in stress relieved state and meet the ASTM F136-02a (ELI Grade 23)/ ASTM F3001 standard.



M2 Series 5 Ti6Al4V

Machine Configuration

M2 Series 5

Single- or dual-laser architecture

Argon gas

Platform heating: 200°C

Powder Chemistry

Ti6Al4V Grade 23 (ELI) powder chemical composition according to ASTM F3001

Particle size: 15-45 µm

For more information, visit: AP&C

Thermal States

As-Built (AB)

Stress Relief (SR1)

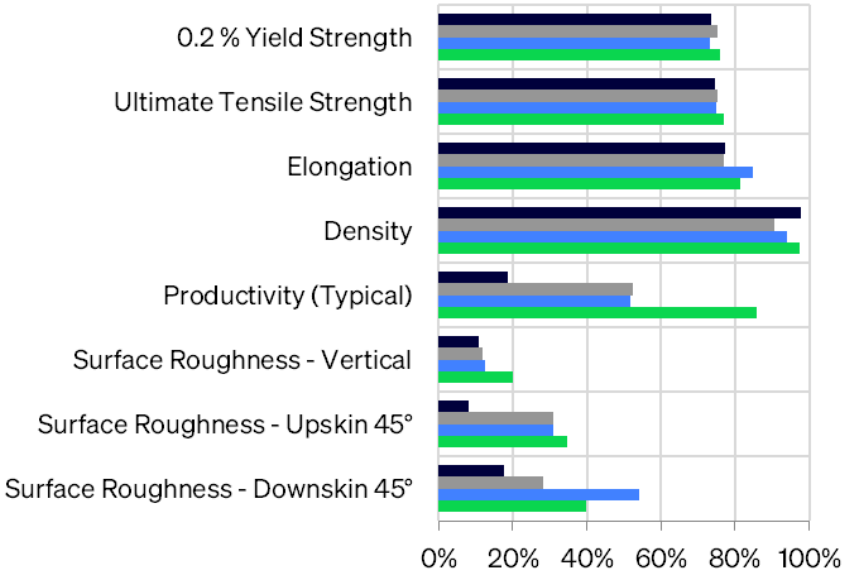
900°C for 1 hour in argon; furnace cooling

Stress Relief (SR2)

840°C for 2 hours in argon; furnace cooling

Parameter Availability and Thermal State Comparison

- Surface Parameter 279 SR1
  400 W, 30 µm layer thickness, rubber recoater
- Surface Parameter 327 SR1
  400 W, 30 µm part layer thickness, 60 µm support layer thickness, rubber recoater
- Balanced Parameter 277 SR1
  400 W, 60 µm layer thickness, rubber recoater
- Balanced Parameter 331 SR1
  400 W, 60 µm layer thickness, steel recoater
- Productivity Parameter 353 SR1
  400 W, 120 µm layer thickness, rubber or steel recoater



Bar plot is generated by normalizing typical material data (containing both horizontal and vertical data) against a range defined for each material family. For titanium-based alloys, the ranges are as follows: 0.2%YS: 0-1250 MPa UTS: 0-1350 MPa, Elongation: 0-20%, Density: 99-100%, Productivity: 5-70 cm^3/h, Surface Quality (all): 5-40 µm. 0% in the bar plot indicates the lower range value, 100% indicates the upper range value.

Surface Parameter 279 / 327 - 400 W / 30 µm

Typical Build Rate

	(cm^3/h)
Typical build rate with coating[1]	17.1
Theoretical melting rate bulk per laser[2]	16.8

[1] Using standard Factory Acceptance Test layout and 2 lasers
[2] Calculated (layer thickness × scan velocity × hatch distance)

Tensile Performance at Room Temperature

Thermal State	Modulus of Elasticity (GPa)		0.2% Yield Strength (MPa)		Ultimate Tensile Strength (MPa)	
	H	V	H	V	H	V
As-Built	111	110	1145	1140	1295	1270
SR1	116	118	920	915	1010	1005

Thermal State	Elongation (%)		Area Reduction (%)	
	H	V	H	V
As-Built	8.0	8.5	27	30
SR1	15.5	15.0	44	42

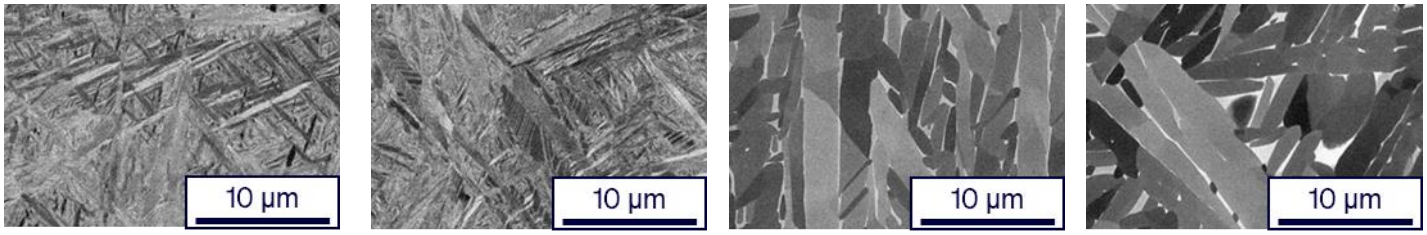
Physical Properties at Room Temperature

	Overhang Surface Roughness, Ra (µm)		
	45°	60°	75°
Upskin	8	8	7
Downskin	12	8	6

Surface Roughness, Ra (µm)	
H	12
V	9

Thermal State	Relative Density (%)		Hardness (HV10)
	H	V	H
As-Built	99.9	99.9	353
SR1	99.9	99.9	334

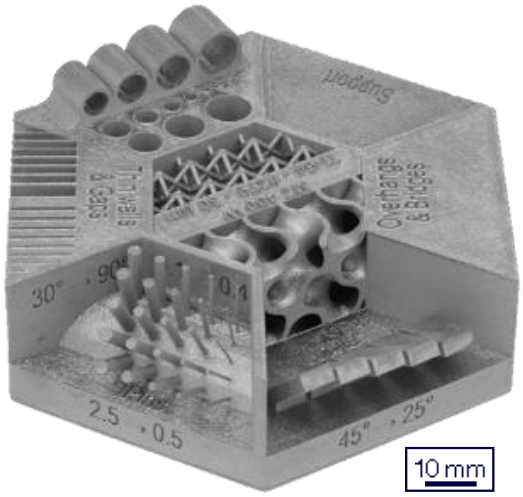
As-Built		SR1	
H	V	H	V



Scanning electron microscope images in As-Built and Stress Relief (SR1) condition as defined previously.

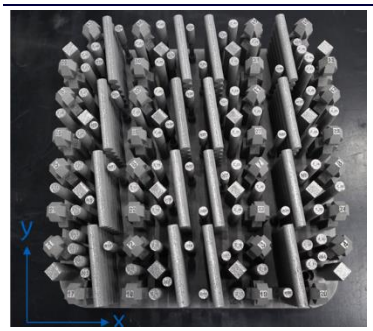
Minimum Feature Resolution

The minimum feature resolution part was designed to demonstrate parameter capability to produce specific features such as minimum wall thickness, minimum gap width, minimum pin diameter, minimum drill hole diameter (horizontal and vertical), minimum unsupported downskin angle, and maximum unsupported bridge length.



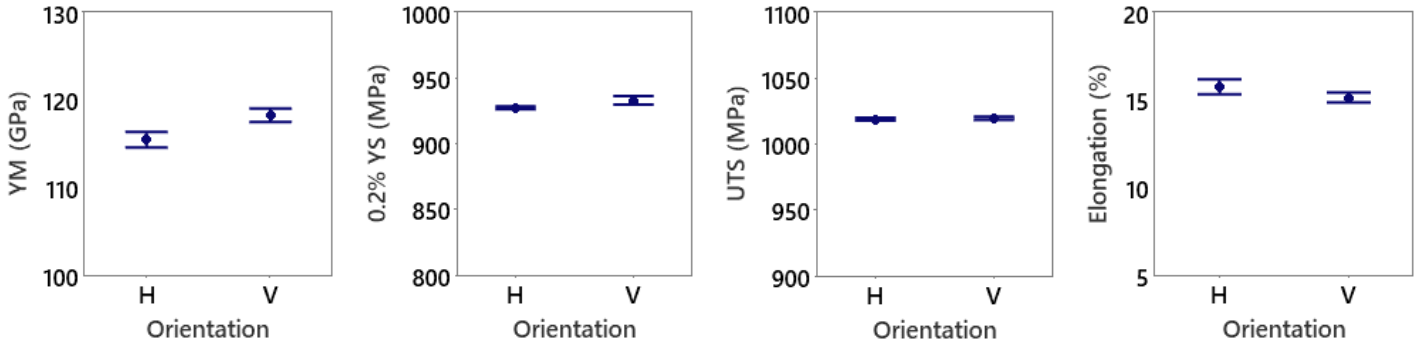
Feature	Result
Minimum Wall Thickness (mm)	0.13
Minimum Gap Width (mm)	0.2
Minimum Pin Diameter (mm)	0.22
Minimum Drill Hole Diameter, V (mm)	0.46
Minimum Drill Hole Diameter, H (mm)	0.47
Minimum Printable Angle (°)	35
Maximum Bridge Length (mm)	5

The platform stability build evaluates relative density, roughness and tensile properties across different positions and orientations. To illustrate the position dependency of the M2 Series 5, the samples were homogenously distributed across the platform on 16 different positions. Regarding surface quality all sides of the specimen, so all orientations with respect to gas flow and optical system, are included in the analysis. Data shown below are dependent on part & print layout as well as batch chemistry variations and thus might deviate from “typical values” given on previous pages.

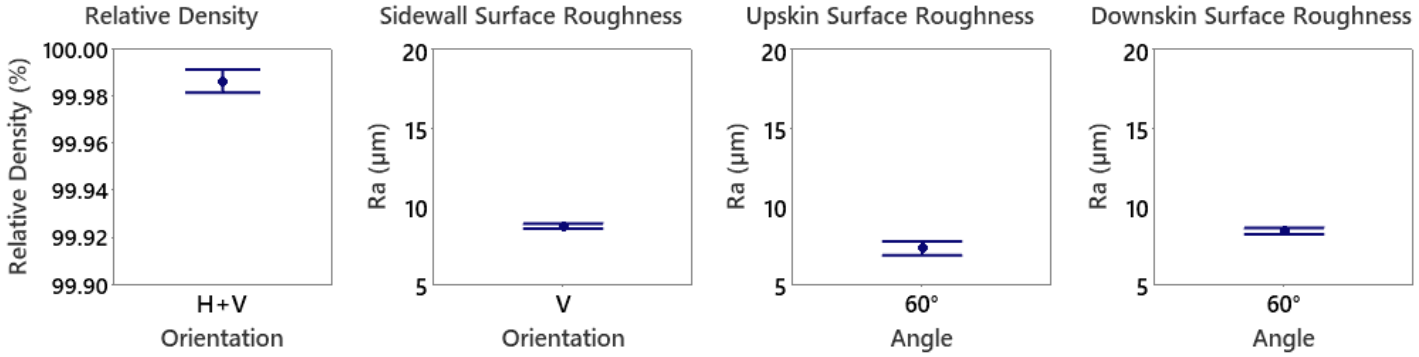


	Sample Size	Mean	Std. Dev.		Sample Size	Mean	Std. Dev.
YM (GPa) H/V - SR1	16/16	115/118	2/1	Rel. Density (%)	32	99.99	0.01
0.2% YS (MPa) H/V - SR1	16/16	927/933	2/6	Sidewall Roughness Ra (µm)	128	8.7	0.8
UTS (MPa) H/V - SR1	16/16	1019/1020	2/2	60° Upskin Roughness Ra (µm)	64	7.3	1.8
Elongation (%) H/V - SR1	16/16	15.7/15.1	0.8/0.5	60° Downskin Roughness Ra (µm)	64	8.4	0.8

Results Platform Stability: Mechanical properties in SR1 condition



Results Platform Stability: Relative Density and Surface Quality



Balanced Parameter 277 - 400 W / 60 µm

Typical Build Rate

	(cm^3/h)
Typical build rate with coating[1]	39.0
Theoretical melting rate bulk per laser[2]	40.4

[1] Using standard Factory Acceptance Test layout and 2 lasers
[2] Calculated (layer thickness × scan velocity × hatch distance)

Tensile Performance at Room Temperature

Thermal State	Modulus of Elasticity (GPa)		0.2% Yield Strength (MPa)		Ultimate Tensile Strength (MPa)	
	H	V	H	V	H	V
As-Built	113	112	1115	1125	1255	1275
SR1	121	118	940	940	1015	1015
SR2	118	119	995	995	1050	1050

Thermal State	Elongation (%)	
	H	V
As-Built	7.0	8.0
SR1	16.0	14.5
SR2	13.5	14.5

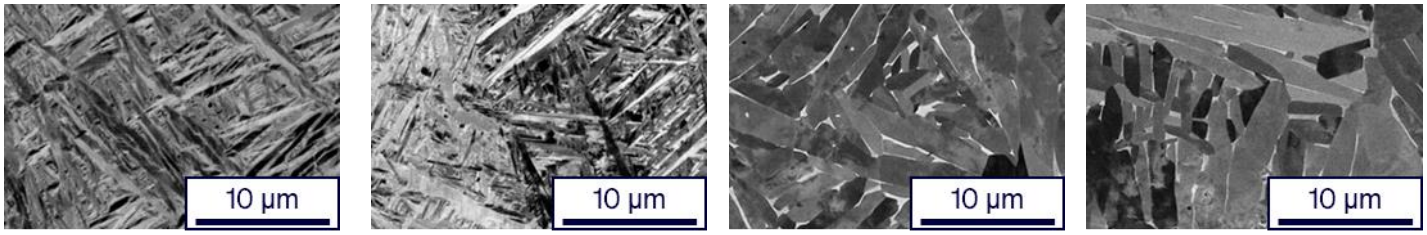
Physical Properties at Room Temperature

	Overhang Surface Roughness, Ra (µm)		
	45°	60°	75°
Upskin	16	13	8
Downskin	15	10	6

Surface Roughness, Ra (µm)	
H	18
V	10

Thermal State	Relative Density (%)		Hardness (HV10)
	H	V	H
As-Built	99.9	99.9	357
SR1	99.9	99.9	342

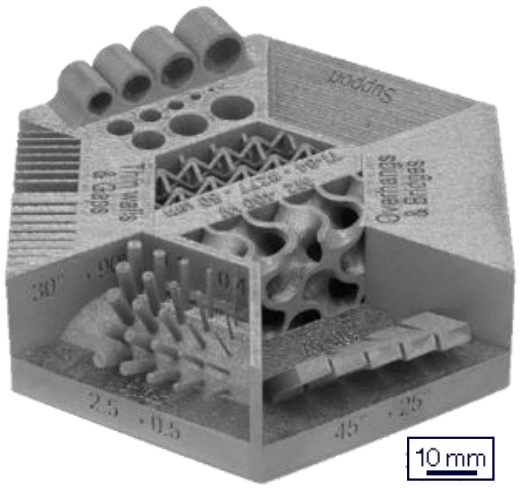
As-Built		SR1	
H	V	H	V



Scanning electron microscope images in As-Built and Stress Relief (SR1) condition as defined previously.

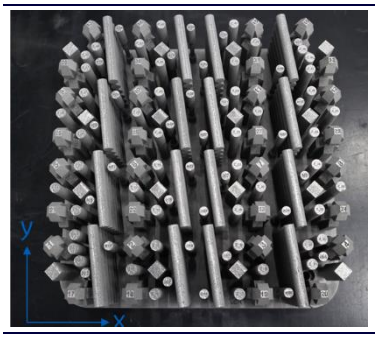
Minimum Feature Resolution

The minimum feature resolution part was designed to demonstrate parameter capability to produce specific features such as minimum wall thickness, minimum gap width, minimum pin diameter, minimum drill hole diameter (horizontal and vertical), minimum unsupported downskin angle, and maximum unsupported bridge length.



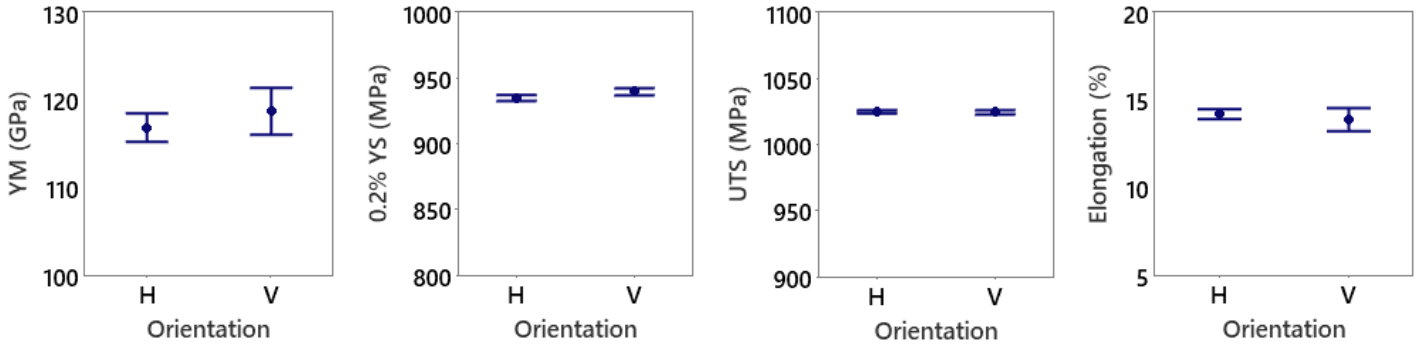
Feature	Result
Minimum Wall Thickness (mm)	0.17
Minimum Gap Width (mm)	0.16
Minimum Pin Diameter (mm)	0.30
Minimum Drill Hole Diameter, V (mm)	0.29
Minimum Drill Hole Diameter, H (mm)	0.41
Minimum Printable Angle (°)	25
Maximum Bridge Length (mm)	5

The platform stability build evaluates relative density, roughness and tensile properties across different positions and orientations. To illustrate the position dependency of the M2 Series 5, the samples were homogenously distributed across the platform on 16 different positions. Regarding surface quality all sides of the specimen, so all orientations with respect to gas flow and optical system, are included in the analysis. Data shown below are dependent on part & print layout as well as batch chemistry variations and thus might deviate from “typical values” given on previous pages.

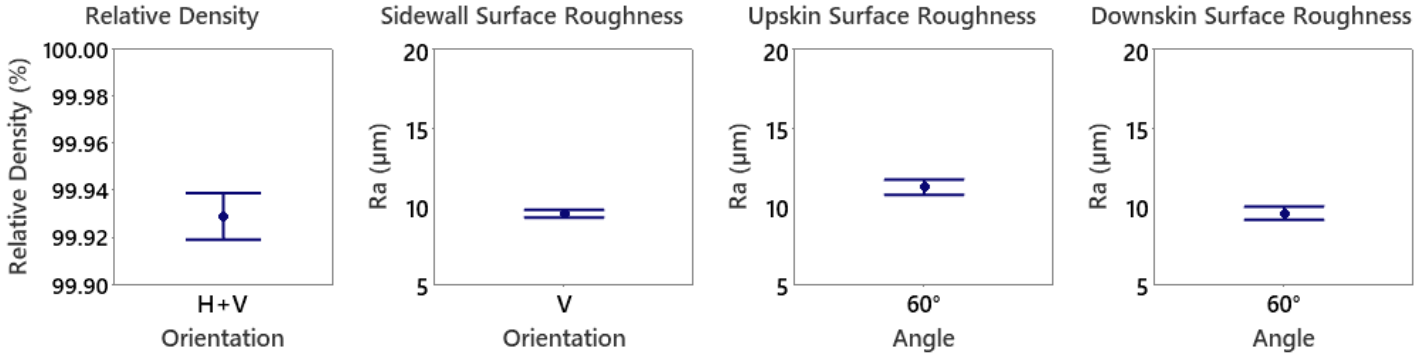


	Sample Size	Mean	Std. Dev.		Sample Size	Mean	Std. Dev.
YM (GPa) H/V - SR1	16/16	117/119	3/5	Rel. Density (%)	32	99.93	0.03
0.2% YS (MPa) H/V - SR1	16/16	935/940	4/5	Sidewall Roughness Ra (µm)	64	9.5	1.0
UTS (MPa) H/V - SR1	16/16	1025/1024	2/3	60° Upskin Roughness Ra (µm)	64	11.7	2.0
Elongation (%) H/V - SR1	16/16	14.2/13.9	0.5/1.3	60° Downskin Roughness Ra (µm)	64	9.6	1.5

Results Platform Stability: Mechanical properties in SR1 condition



Results Platform Stability: Relative Density and Surface Quality



Balanced Parameter 331 - 400 W / 60 µm

Typical Build Rate

	(cm^3/h)
Typical build rate with coating[1]	38.6
Theoretical melting rate bulk per laser[2]	40.4

[1] Using standard Factory Acceptance Test layout and 2 lasers
[2] Calculated (layer thickness × scan velocity × hatch distance)

Tensile Performance at Room Temperature

Thermal State	Modulus of Elasticity (GPa)		0.2% Yield Strength (MPa)		Ultimate Tensile Strength (MPa)	
	H	V	H	V	H	V
As-Built	111	112	1130	1150	1255	1280
SR1	114	118	915	915	1015	1005

Thermal State	Elongation (%)		Area Reduction (%)	
	H	V	H	V
As-Built	8.5	8.0	29	36
SR1	16.5	17.0	44	45

Physical Properties at Room Temperature

	Overhang Surface Roughness, Ra (µm)		
	45°	60°	75°
Upskin	16	13	10
Downskin	25	15	11

Surface Roughness, Ra (µm)	
H	18
V	10

Thermal State	Relative Density (%)		Hardness (HV10)
	H	V	H
As-Built	99.9	99.9	351
SR1	99.9	99.9	334

Productivity Parameter 353 - 400 W / 120 µm

Typical Build Rate

	(cm^3/h)
Typical build rate with coating[1]	60.8
Theoretical melting rate bulk per laser[2]	56.2

[1] Using standard Factory Acceptance Test layout and 2 lasers
[2] Calculated (layer thickness × scan velocity × hatch distance)

Tensile Performance at Room Temperature

Thermal State	Modulus of Elasticity (GPa)		0.2% Yield Strength (MPa)		Ultimate Tensile Strength (MPa)	
	H	V	H	V	H	V
As-Built	113	113	1115	1160	1225	1275
SR1	116	119	945	950	1035	1035

Thermal State	Elongation (%)		Area Reduction (%)	
	H	V	H	V
As-Built	8.5	6	34	33
SR1	16	16.5	45	47

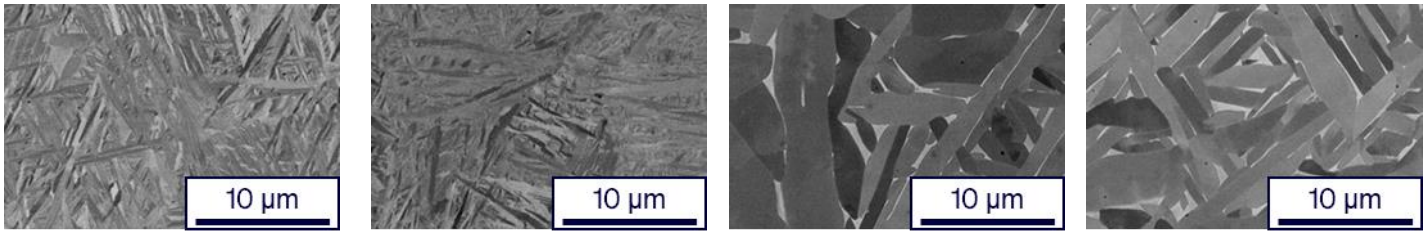
Physical Properties at Room Temperature

	Overhang Surface Roughness, Ra (µm)		
	45°	60°	75°
Upskin	18	14	13
Downskin	19	13	10

Surface Roughness, Ra (µm)	
H	10
V	12

Thermal State	Relative Density (%)		Hardness (HV10)
	H	V	H
As-Built	99.9	99.9	365
SR1	99.9	99.9	345

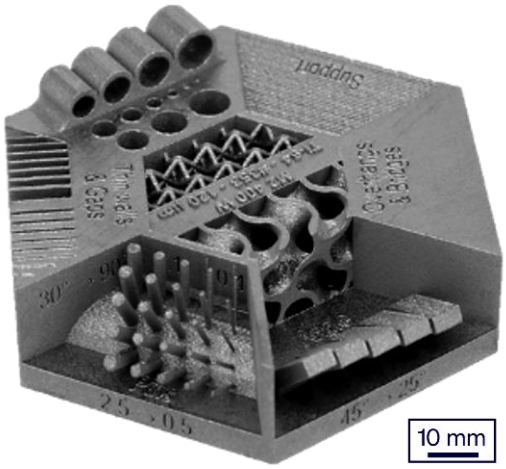
As-Built		SR1	
H	V	H	V



Scanning electron microscope images in As-Built and Stress Relief (SR1) condition as defined previously.

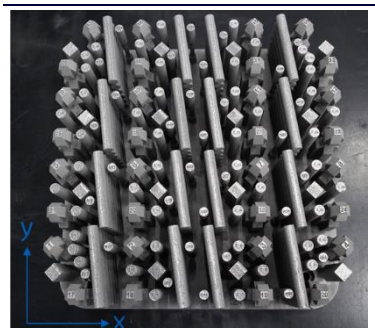
Minimum Feature Resolution

The minimum feature resolution part was designed to demonstrate parameter capability to produce specific features such as minimum wall thickness, minimum gap width, minimum pin diameter, minimum drill hole diameter (horizontal and vertical), minimum unsupported downskin angle, and maximum unsupported bridge length.



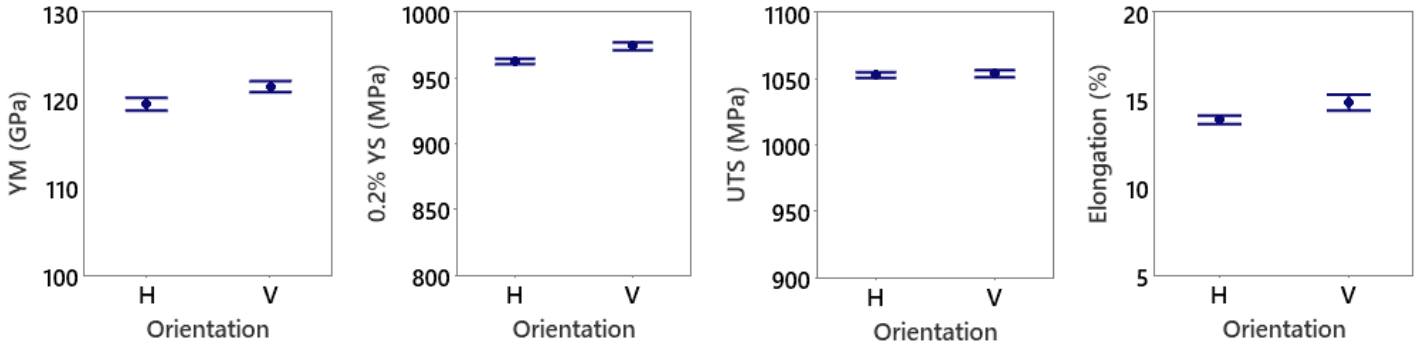
Feature	Result
Minimum Wall Thickness (mm)	0.28
Minimum Gap Width (mm)	0.10
Minimum Pin Diameter (mm)	0.29
Minimum Drill Hole Diameter, V (mm)	0.34
Minimum Drill Hole Diameter, H (mm)	0.35
Minimum Printable Angle (°)	25
Maximum Bridge Length (mm)	5

The platform stability build evaluates relative density, roughness and tensile properties across different positions and orientations. To illustrate the position dependency of the M2 Series 5, the samples were homogenously distributed across the platform on 16 different positions. Regarding surface quality all sides of the specimen, so all orientations with respect to gas flow and optical system, are included in the analysis. Data shown below are dependent on part & print layout as well as batch chemistry variations and thus might deviate from “typical values” given on previous pages.

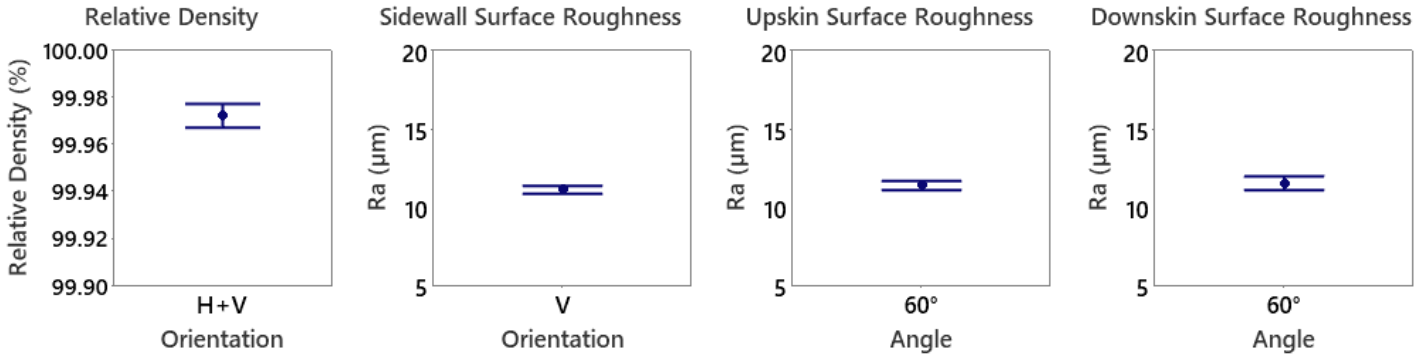


	Sample Size	Mean	Std. Dev.		Sample Size	Mean	Std. Dev.
YM (GPa) H/V - SR1	16/16	120/122	1/1	Rel. Density (%)	32	99.97	0.01
0.2% YS (MPa) H/V - SR1	16/16	963/974	4/6	Sidewall Roughness Ra (µm)	64	11.1	1.0
UTS (MPa) H/V - SR1	16/16	1053/1054	4/5	60° Upskin Roughness Ra (µm)	64	11.4	1.2
Elongation (%) H/V - SR1	16/16	13.9/14.8	0.4/0.9	60° Downskin Roughness Ra (µm)	64	11.5	1.8

Results Platform Stability: Mechanical properties in SR1 condition



Results Platform Stability: Relative Density and Surface Quality



COLIBRIUM ADDITIVE
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13 Al

22 Ti | 24 Cr | 26 Fe | 27 Co | 28 Ni | 29 Cu

L-PBF Ti6Al4V Grade 23

Mesh+ Parameters for Colibrium Additive's M2 Series 5

Titanium Ti6Al4V Grade 23 (ELI)

Titanium shows a high corrosion resistance and proven biocompatibility and has been employed successfully in human implant applications in contact with soft tissue and bone for decades.

Porous (trabecular) structures are very common for AM-manufactured medical implants. The open titanium architecture results in open structures that lead to enhanced osseointegration and allows adjusting the final device characteristics (density, stiffness).

M2 Series 5 Ti6Al4V Mesh+ Parameters

The Mesh+ parameters enable the user to design porosity and pore size, as well as interconnectivity of trabecular structures to allow for enhanced initial fixation and bone ingrowth. The parameters further provide the user with an exceptional balance of high grade of detail and high productivity.

The Mesh+ parameters can be used in conjunction with the Colibrium Additive M2 Series 5 Ti6Al4V parameters to create parts with both solid and mesh volumes to create hybrid components.

M2 Series 5 Ti6Al4V

Machine Configuration

M2 Series 5

Single- or dual-laser architecture

Argon gas

Platform heating: 200°C

Powder Chemistry

Ti6Al4V Grade 23 powder chemical composition according to ASTM F3001

Particle size: 15-45 µm

For more information, visit: AP&C

Thermal States

As-Built

Stress Relief (SR1)

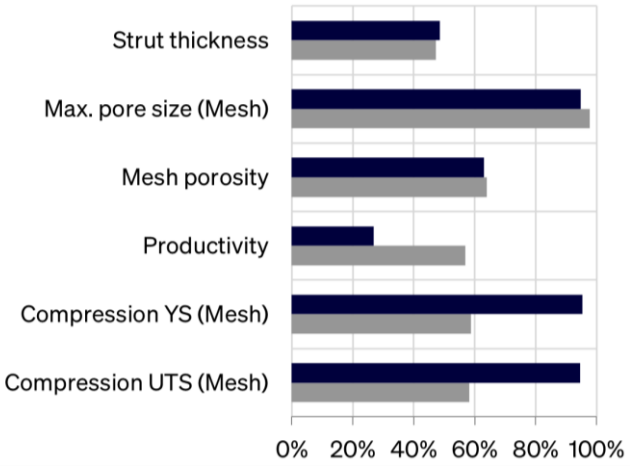
900°C for 1 hour in argon; furnace cooling

Hot Isostatic Pressing (HIP)

900°C, 2 hours, pressure 100 MPa

Parameter Availability and Thermal State Comparison

- Surface Mesh Parameter 284 SR1
  400 W, 30 µm layer thickness, rubber recoater
- Balanced Mesh Parameter 278 SR1
  400 W, 60 µm layer thickness, rubber recoater



Bar Plot is generated by normalizing typical material data (containing both horizontal and vertical data) against a range defined for each material family. For titanium-based alloys, the ranges are as follows: Compression UTS (Mesh): 0-110 MPa, 0.2%YS (Mesh): 0-85 MPa, Productivity: 5-70 cm³/h, Mesh porosity: 0-100 %, Max. pore size (Mesh): 0-500 µm, Strut thickness: 0-500 µm. 0% in the Bar Plot indicates the lower range value, 100% indicates the upper range value

Surface Mesh+ Parameter - 400 W / 30 µm

Typical Build Rate

Item	(cm^3/h)
Theoretical melting rate bulk per laser[2]	17.5

[1] Using standard Factory Acceptance Test layout and 2 lasers
[2] Calculated (layer thickness × scan velocity × hatch distance)

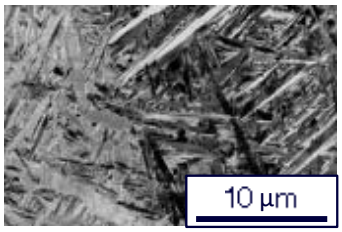
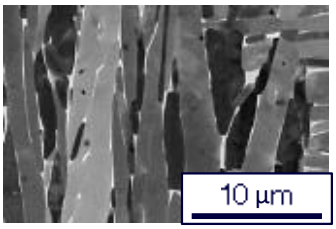
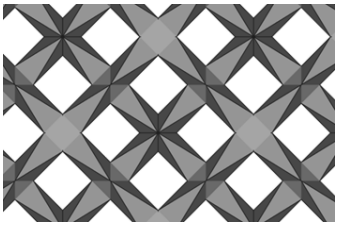
Compression Strength of Mesh Structure**

Thermal State	Modulus of Elasticity (Compression) (GPa)	Yield Strength (Compression) (MPa)	Compressive Strength (MPa)
As-Built	2.2	80	104
SR1	2.5	81	104
HIP	2.3	76	100

Mesh Dimensions**

Thermal State	Mesh Porosity (%)	Strut Thickness (µm)	Max. Grid Size (µm)
As-Built	63	250	480

Microstructure + CAD images

As-Built	SR1	CAD	SEM Image (post-processed)
V	V	Mesh design** V	V
			

Scanning electron microscope images in As-Built and Stress Relief (SR1) condition as defined previously.
** Data demonstrating results of special mesh design. Different designs could lead to changes in properties.

Balanced Mesh+ Parameter - 400 W / 60 µm

Typical Build Rate

Item	(cm^3/h)
Theoretical melting rate bulk per laser[2]	36.9

[1] Using standard Factory Acceptance Test layout and 2 lasers
[2] Calculated (layer thickness × scan velocity × hatch distance)

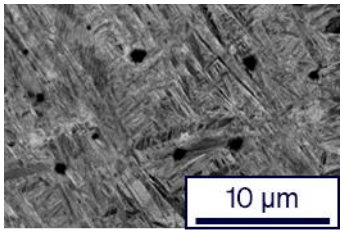
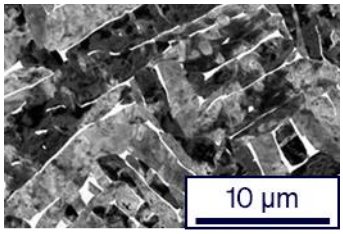
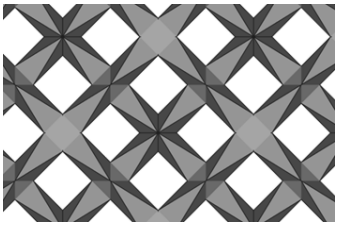
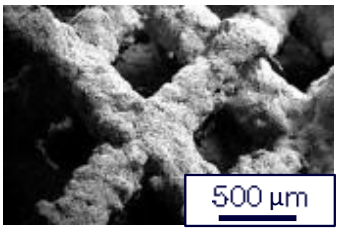
Compression Strength of Mesh Structure**

Thermal State	Modulus of Elasticity (Compression) (GPa)	Yield Strength (Compression) (MPa)	Compressive Strength (MPa)
As-Built	1.2	51	60
SR1	1.3	50	60
HIP	1.3	47	64

Mesh Dimensions**

Thermal State	Mesh Porosity (%)	Strut Thickness (µm)	Max. Grid Size (µm)
As-Built	64	240	490

Microstructure + CAD images

As-Built	SR1	CAD	SEM Image (post-processed)
V	V	Mesh design** V	V
			

Scanning electron microscope images in As-Built and Stress Relief (SR1) condition as defined previously.
** Data demonstrating results of special mesh design. Different designs could lead to changes in properties.

Data Sheet Nomenclature and Notation

ELI: Extra Low Interstitials.

H: Horizontal, perpendicular to build direction.
V: Vertical, parallel to build direction.
Other angles are measured from horizontal.

Roughness measurements have been performed according to DIN EN ISO 4287 and DIN EN ISO 4288. In general analysis of the surface quality is strongly dependent on the methodology used and therefore deviations might be observed depending on methodology used. Vertical and horizontal sidewalls have been characterized using a tactile system, overhangs using an optical system.

Tensile evaluations were performed according to ASTM E8 or E21, depending on test temperature.

Minimum features have been characterized using a coordinate measuring machine (CMM) and an optical microscope.